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DEPARTMENT OF ENERGY

LSA
LOW-COST SOLAR ARRAY

PROJECT

Project QUARTERLY REPORT - 7

FOR THE PERIOD OCTOBER 1977 - DECEMBER 1977

5101-81

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
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The JPL Low-cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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SECTION I

INTRODUCTION AND PROJECT OVERVIEW

A. INTRODUCTION

This report describes the activities of the Low-Cost Silicon Solar Array Project during the period October through December, 1977. The LSSA Project is assigned responsibility for advancing silicon solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this and the progress that was made during the quarter.

The Project objective is to develop the national capability to produce low-cost, long-life photovoltaic arrays at a rate greater than 500 megawatts per year and a price of less than $500* per kilowatt peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

B. PROJECT OVERVIEW

At the December Project Integration Meeting, the Solar Array Manufacturing Industry Costing Standards (SAMICS) were disseminated and a "strawman" poly-to-module manufacturing process sequence based on SAMICS was presented. Development of the SAMIS II computer program continued during the quarter and a contract was let to update and extend the SAMICS data base for eventual incorporation into the SAMIS model.

Five array design concepts were selected for detailed cost analysis and augmented SOMET tapes for eleven selected cities were acquired to verify the total horizontal insolation by the Liu and Jordan analytical characterization of solar insolation.

In the task for developing processes for semiconductor grade silicon production, one contractor continued studies of the use of a $SiF_4/(SiF_2)_x$ transport process; the data showed a polymer conversion efficiency greater than 59% and an overall efficiency of 78.5%. Another contractor, working on production of silicon by Zn reduction of $SiCl_4$, prepared a detailed material and energy flow sheet for a 50 MT/yr Experimental Process System Development Unit. A third contractor found that higher operating pressures substantially increased conversion to $SiHCl_3$ in the hydrogenation of $SiCl_4$. The results greatly improve the practicality of the overall process for the production of SiH_4.

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*In 1975 dollars

The feasibility of using continuous high temperature diffusion flames of alkali metals and silicon halides was tested using thermochemical calculations which indicated that reactions between either Na or K and any of the silicon halides are strongly exoergic and that Si is the only condensed phase in any of the equilibrium product distributions. In another program, using a non-equilibrium plasma jet for the reduction of silicon chlorides, amorphous, polycrystalline, and some preferred growth silicon deposits were obtained.

A new contract is for testing the feasibility of using bromosilanes in a high-volume, high-velocity, continuous reduction process.

In the development of the process using a submerged arc furnace and unidirectional solidification, B and P are the impurities of primary concern, the main source being the C-redundant.

The feasibility of using a two-step process in which Na is used to reduce SiF_4 obtained from H_2SiF_6, a byproduct of the fertilizer industry, to silicon, and the Si further purified, is being determined.

Investigation continued of the effects of various process, impurities, and process-impurity interactions on the performance of solar cells.

Work also continued on the transmission line equivalent circuit model of a solar cell. A graphic display program was coded to display a cell parameter, such as lifetime, as a function of position in the cell at a terminal. This display capability was expected to significantly aid in the basic understanding of the parameters which control the efficiency of a cell under operating conditions.

A new program was designed to develop a mathematical model, and a computer code created based on the model, which will allow the prediction of the product distribution in chemical reactors in which gaseous Si compounds are converted to condensed-phase Si.

Economic analysis continued with the major activities focused on the preliminary process design of the silane process.

Working on edge-defined, film-fed growth, a contractor reported that further analysis of the EFG ribbon growth scenario using SAMICS interim price estimation guidelines showed that a double five-ribbon furnace of the type used for this study can produce sheet material at <$20/m^2$. Working in the same technology area, another contractor installed a 100-mm wide ribbon growth furnace and grew a 94-mm wide ribbon; however, the ribbon shattered upon withdrawal from the furnace.

In work with laser zone ribbon growth, modifications have increased laser output power, and ribbon can now be grown at 10 cm/min (for 2 cm-wide ribbon stock). This increase in growth velocity is accompanied by a new growth phenomenon in the form of dendritic growth. Dendritic web process studies were oriented toward developing growth configurations which produced web crystals having low residual stress levels.

In the ingot technology area, fabrication began on a prototype large capacity multiple blade slurry saw, and final concept and design were nearly completed on a bladehead which will tension up to 1000 blades and cut a 50 cm long silicon ingot of up to 12 cm in diameter. An add-on to another contract will examine heat flow and other thermal parameters to increase the growth rate of shaped ingots.

Significant improvement was reported in single crystal grain growth in experiments where a small section of an EFG-grown silicon ribbon is used to seed a silicon-on-ceramic coating. A new contract was negotiated for a program to develop and apply epitaxial growth techniques to the fabrication of efficient solar cells on low-cost forms of silicon sheet.

During the quarter, materials surveys continued to establish a list of candidate low-cost, long-life materials and materials design concepts for encapsulation. Reports identified common construction elements and suitable and unsuitable materials. Studies also continued on developing a methodology for making confident predictions of encapsulant performance at any exposure site in the United States with recent emphasis on the power output of solar cells under accelerated test conditions and in outdoor exposures. Modifications to an electrostatic bonder continued and four Type II electrostatically bonded, electrically functional modules were delivered to JPL for testing.

In another program, efforts to ion-plate moisture and corrosion barrier coatings of various ceramic oxides were reported to be only partially successful, although the cause of the problem has now been identified. Other investigations during the quarter centered on RTV silicone rubber/glass bond strength and demonstrated that the effect of moisture on adhesion can be predicted quantitatively. The same contractor has begun a feasibility study on the use of ellipsometry and ultrasonics as possible techniques for non-destructive evaluation of adhesion in photovoltaic modules. Experiments were also completed on the effect of ultraviolet exposure with the results expected to provide information on the potential for ultraviolet stabilization via copolymerization.

In the Production Process and Equipment Area, the major thrust of the process assessment phase has been completed and four areas of emphasis for the development phase suggested. Nine one-year contracts were awarded for Phase II Process Development. The advanced module development effort is concentrating on evaluating various design, manufacturing, and cost parameters.

The Engineering Area continued analysis and testing of solar array modules in conjunction with the development of future module and array design criteria and test methods, and support of large-scale procurements in the area of engineering interfaces. Two recently started module requirement contracts proceeded on schedule. One contract is emphasizing optimization with respect to module structural costs and the other is exploring the advantages and disadvantages of enclosing modules in a self-supporting transparent enclosure.

In order to provide test hardware to support the development of improved environmental qualification test procedures, 60 reduced-size versions of the Block II modules were obtained from each manufacturer. Using these mini-modules instead of full size modules for destructive tests results in a substantial cost savings.

Thermal performance testing of various module designs continued during the quarter, and one series of tests was conducted to demonstrate the magnitude of potential increases in module output power. Tests were conducted by cooling the modules with water. Studies were also initiated on causes of delamination in module designs with the objective of correlating chemical or physical properties of the interface between encapsulant and substrate with the onset of delamination. An investigation of module soiling characeristics was also begun, with a portion of the investigation involving a cooperative effort with the Los Angeles County Air Quality Management District in providing data on total suspended particulates at eight air quality sampling sites. Another new study is investigating the application of anti-static coatings and treatments for module encapsulants.

In the Operations Area, Block II module deliveries totaled 10.6 kW, and the selection and allocation part of the procurement process for Block III was completed. Environmental testing for large-scale production (Task 5) modules centered on qualification tests on 23 one-kW sample modules representing three suppliers. Results were generally satisfactory for all modules. Task 4 tested ten modules from one manufacturer and all passed environmental tests satisfactorily although a total of four cells cracked. Commercial modules from two manufacturers were also tested, with modules from one manufacturer performing significantly better than those from the other. Two hundred additional cells were received from another manufacturer, half of them of the evaporated contact type (aerospace) and the other half the improved printed contact type (Process B). After humidity tests, the aerospace cells showed very little change but the output by Process B cells appeared to improve by a few percent.

Field testing centered on the data system which is now capable of obtaining I-V data on any module in the field. Deployment of all the Block I and II modules at JPL, Table Mountain, and Goldstone was completed.

Greater understanding was achieved during the quarter of the solar cell photon instability problem, although the necessary changes in the manufacturing process to eliminate the problem were not clearly identified.

SECTION II

PROJECT ANALYSIS AND INTEGRATION AREA

A. ARRAY TECHNOLOGY COST ANALYSIS

1. Uniform Costing Methodology

SAMICS, the Solar Array Manufacturing Industry Costing Standards, were disseminated at the December Project Integration Meeting. Complete documentation of the preparation of input data and of the application of the manual calculation procedure is contained in the following project documents, all of which can be obtained from the LSA Data Center, mailstop 506-451.

JPL Document No. 5101-44, "SAMICS Input Data Preparation"

ERDA/JPL-954800-77/2.1, "Cost Account Catalog" by Theodore Barry and Associates

JPL Document 5101-59, "SAMICS Usage Update Number 1," published February 1, 1978

JPL Document 5101-15, "SAMICS Workbook"

JPL Document 5101-33, "Interim Price Estimation Guidelines"

JPL Forms 3037-S through 3041-S

2. Manufacturing Sequence Price Estimation

A "strawman" poly-to-module manufacturing process sequence to produce $2/W$_{pk}$ modules at 20 megawatts of annual production was developed and analyzed by the SAMICS procedure, producing the results shown in Figures 2-1 and 2-2. These data were presented at the December 1977 Project Integration Meeting. Sensitivity studies will be presented in a forthcoming project document.

3. Industry Simulation

Development of the SAMIS III computer program continued. Design, coding, and compilation were essentially complete. Testing and debugging were under way.

A contract was let to Theodore Barry and Associates to update and extend the SAMICS data base and the development of models of sales and marketing, and of warehousing and distribution for eventual incorporation into the SAMIS model.

PROCESS	PRICE	DIRECT COSTS	INDIRECT COSTS		
			PROFIT	TAXES	OTHER
SILICON AT 21 $/kg	0.381	0.381			
CRYSTAL GROWTH	0.770	0.430	0.055	0.095	0.190
GRINDING/CROPPING	0.017	0.010	0.001	0.002	0.004
SLURRY SAWING	0.179	0.091	0.012	0.024	0.052
WAFER TESTING	0.015	0.007	0.001	0.002	0.005
MECHANICAL BRUSH CLEANING	0.033	0.019	0.002	0.005	0.007
RINSING AND CLEANING	0.005	0.003	0.000	0.001	0.001
SPIN ON BORON DOPANT	0.072	0.050	0.002	0.009	0.011
DIFFUSION WITH $POCL_3$	0.018	0.007	0.001	0.003	0.007
PLATING AREA MASK	0.016	0.007	0.001	0.003	0.005
PATTERN ETCH	0.008	0.004	0.001	0.001	0.002
ELECTROLESS GOLD/NICKEL PLATE	0.084	0.062	0.001	0.007	0.014
REMOVE MASK	0.005	0.002	0.000	0.001	0.002
LASER SCRIBED WAFERS	0.022	0.008	0.002	0.004	0.008
SOLDER DIPPED CELLS	0.008	0.003	0.001	0.002	0.002
ELECTRICAL TEST	0.007	0.002	0.001	0.002	0.002
INTERCONNECT	0.086	0.061	0.001	0.008	0.016
ELECTRICAL TEST	0.004	0.001	0.000	0.001	0.002
SOLDER BUSBARS	0.077	0.056	0.001	0.006	0.014
GLASS MODULE ASSEMBLY	0.108	0.077	0.001	0.010	0.020
GASKET AND FRAME	0.077	0.055	0.001	0.007	0.014
TEST AND PACK	0.008	0.002	0.001	0.002	0.003
TOTAL MODULE (ASSUMING 21 $/kg Si)	2.000	1.338	0.086	0.195	0.381

PRICES ARE VALUE ADDED, IN $ 1975/WPK

Figure 2-1. $2/Watt Technology "Strawman" Costs

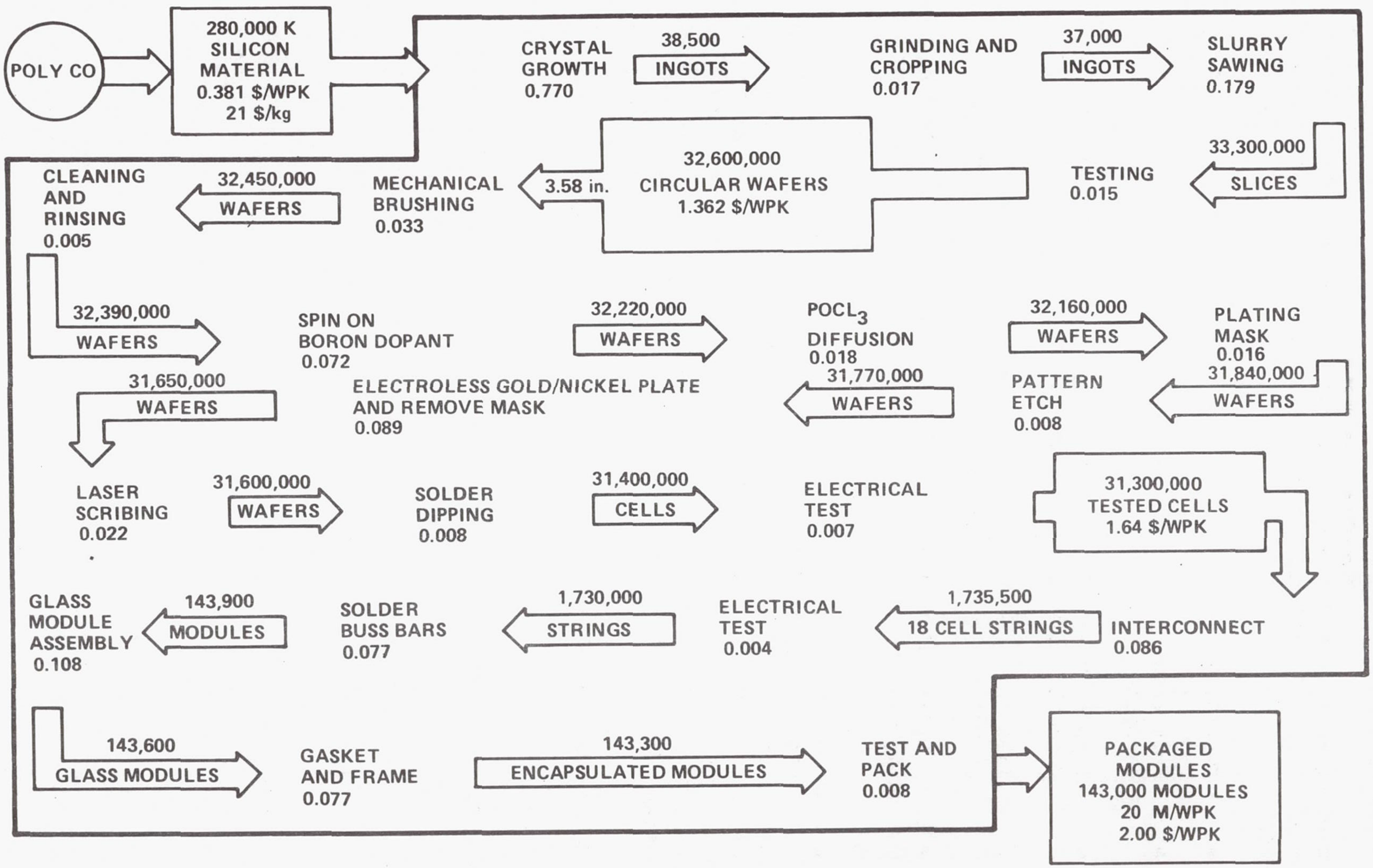


Figure 2-2. $2/Watt Technology "Strawman" Manufacturing Process Sequence Value Added Cost Analysis

B. ARRAY LIFE CYCLE ANALYSIS

1. Bechtel presented 13 array conceptual designs for JPL's reviews on October 21, 1977. Five design concepts were selected for detailed cost analysis:

- Horizontal array: Modules rest near ground without structures.
- Rack array: Modules rest on raised, rack-like structures on separate foundations.
- Tandem array: Modules rest on raised structures sharing foundations with reflectors (a potential advantage).
- Tilt adjusted array: Modules rest on raised and separate structures and foundations with lift and lock mechanisms.
- Diurnal adjusted array: Modules rest on structures supported by separate, single pedestal.

2. Augmented SOMET tapes for 11 selected U.S. cities were acquired to verify the total horizontal insolation by the Liu and Jordon analytical characterization of solar insolation. Direct normal solar insolation data for Albuquerque, New Mexico, were acquired to verify another portion of the Liu and Jordan model. A verified Liu and Jordon model is a useful form of representing solar insolation profile instead of weather tapes in modeling performance of large solar photovoltaic arrays.

C. ECONOMICS/INDUSTRIALIZATION

Completion of a major analysis, "Historical Evidence of Importance to the Industrialization of Flat-Plate Silicon Photovoltaic Systems," has been announced and will be published as an LSA Project document.

SECTION III

TECHNOLOGY DEVELOPMENT AREA

A. SILICON MATERIAL TASK

The objective of the Silicon Material Task is to establish by 1986 an installed plant capability for producing Si, suitable for solar cells, at a rate equivalent to 500 megawatts (peak) of solar arrays per year and at a price of less than $10 per kilogram. The program formulated to achieve this objective is based on the conclusion that the price goal cannot be reached if the process used is essentially the same as the present commercial process for producing semiconductor-grade Si. Consequently, it is necessary different processes be developed for producing either semiconductor-grade Si or a less pure and less costly, but utilizable, Si material (i.e., a solar-cell-grade Si).

1. Technical Goals

Solar cells are presently fabricated from semiconductor-grade Si, which has a market price of about $65 per kilogram. A drastic reduction in price of material is necessary to meet the economic objectives of the LSSA Project. One means for meeting this requirement is to devise a process for producing a Si material which is less pure than semi-conductor-grade Si. However, the allowance for the cost of Si material in the overall economics of the solar arrays for LSSA is dependent on optimization trade-offs, which concomitantly treat the price of Si material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for the optimization trade-offs concurrently with the development of high-volume, low-cost processes for producing Si.

2. Organization and Coordination

The Silicon Material Task effort is organized into five phases. As Table 3-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade Si will be demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells will be investigated. This body of information will serve as a guide in developing and assessing processes (in Part III) for the production of solar-cell-grade Si. The process developments in Parts I and III will be accomplished through chemical reaction, chemical engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various Si-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies and the most promising processes will have been selected.

Phase II will be to obtain process scale-up information. This will be derived from experiments and analyses involving mass and energy balances, process flows, kinetics, mass transfer, temperature and pressure effects, and operating controls. The basic approach will be to provide fundamental scientific and engineering information from which valid extrapolations usable for plant design can be made; applicable scale-up correlations will also be used. This body of scale-up information will then provide the necessary basis for the design, construction, and operation of Experimental Process System Development Units (EPSDU).

Since the installation and operation of a commercial chemical process plant that incorporates a new process involves high risks, EPSDU will be used to obtain technical and economic evidence of large-scale production potential. In the EPSDU phase (i.e., Phase III) there will be opportunities to correct design errors; to determine energy consumption; to establish practical operating procedures and production conditions for process optimization and steady state operation; and to more realistically evaluate the requirements for instrumentation, controls, and on-line analyses.

In the final phase of the Silicon Material Task (i.e., Phase IV), a full-scale commercial plant capable of meeting the production objective will be designed, installed, and operated. The EPSDU and the commercial plant will be operated concurrently for some time so as to permit the use of the EPSDU for investigations of plant operations, i.e., for problem-solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of the Silicon Material Task will be conducted in supporting efforts. These supporting subtasks will be accomplished under contract and by an in-house JPL program.

3. Silicon Material Task Contracts

Seventeen contracts are in progress and are listed in Table 3-1.

4. Silicon Material Task Technical Background

The objectives of Phase I of the Silicon Material Task are shown in Table 3-2.

a. Processes for Producing Semiconductor-Grade Silicon.

1) Production of Si by Zn Reduction of $SiCl_4$ - Battelle. The contract with Battelle Memorial Institute is for development of the reaction for the Zn reduction of $SiCl_4$ using a fluidized bed reactor as an economical means for producing Si. Based on calculations by Battelle and Lamar University, this process has the potential for a total product cost between $9.12 and $9.68/kg Si for a 1000 metric ton/year plant.

2) Production of Si From SiH_4 Prepared by Redistribution of Chlorosilanes - Union Carbide. The Union Carbide contract is for the development of processes for the production of SiH_4 and for the subsequent

Table 3-1. Silicon Material Task Contractors

Contractor	Technology Area
AeroChem Research Princeton, New Jersey (JPL Contract No. 954560)	Nonequilibrium plasma jet process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954777)	Si halide-alkali metal flames process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954862)	Model of silicon reactions
Battelle Columbus, Ohio (JPL Contract No. 954339)	$Zn/SiCl_4$ fluid bed reactor process
Dow Corning Hemlock, Michigan (JPL Contract No. 954559)	Electric arc furnace process
Lamar University Beaumont, Texas (JPL Contract No. 954343)	Technology and economic analyses
Material Research Salt Lake City, Utah (JPL PO No. JR-672583)	X-ray analysis of silicon wafers
Motorola Phoenix, Arizona (JPL Contract No. 954442)	SiF_4/SiF_2 transport process
National Bureau of Standards Washington, D.C. (JPL Interagency WO No. 8604)	Impurity concentration measurements
Northrop Research Hawthorne, California (JPL Contract No. 954614)	Lifetime and diffusion length measurements
Sah, C.T. Assoc. Urbana, Illinois (JPL Contract No. 954685)	Effects of impurities

Table 3-1. Silicon Material Task Contractors (Continuation 1)

Contractor	Technology Area
Schumacher, J.C. Oceanside, California (JPL Contract No. 954914)	High-velocity continuous flow reactor process
Spectrolab Sylmar, California (JPL Contract No. 954694)	Measurements of effects of impurities on solar cells
Stanford Research Institute Menlo Park, California (JPL Contract No. 954471)	Na reduction of SiF_4 process
Union Carbide Sisterville, West Virginia (JPL Contract No. 954334)	Silane/Si process
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954331)	Effects of impurities on solar cells
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954589)	Plasma arc heater process

deposition of Si from SiH_4. The SiH_4 process includes systems for the redistribution of chlorosilanes and the hydrogenation of the by-product $SiCl_4$ to $SiHCl_3$, which can be used as a feed for redistribution. The free space reactor and the fluidized bed reactor are techniques being investigated as the means for Si deposition.

3) Production of Si by SiF_4/SiF_2 Transport - Motorola. The Motorola contract is for the development of a process for the conversion of metallurgical-grade Si into semiconductor-grade Si using $SiF_4/(SiF_2)_x$ transport purification reaction steps.

b. Effects of Impurities and Processing on Solar Cell Performance

1) Determination of the Effects of Impurities and Process-Steps on Properties of Si and the Performance of Solar Cells - Westinghouse/Dow Corning. Phase II of this contract consists of five tasks: (1) The effects of processing-steps, such as heat treatment, gettering, and crystal growth parameters, will be determined in conjunction with the impurity effects.

Table 3-2. Organization of the Silicon Material Task Effort

Phase/Part	Objective
Phase I	Demonstrate the technical feasibility and practicality of processes for producing Si.
Part I	Establish the practicality of a process capable of high-volume production of semiconductor-grade Si.
Part II	Investigate the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells.
Part III	Establish the practicality of a process capable of high-volume production of solar-cell-grade Si.
Part IV	Evalute the relative commercial potential of the Si-production processes developed under Phase I.
Phase II	Obtain process scale-up information.
Phase III	Conduct EPSDU operations to obtain technical and economic evidence of large-scale production potential.
Phase IV	Design, install, and operate a full-scale commercial plant capable of meeting the production objective.

(2) The combined effects of impurities and high B concentrations on solar cell performance will be examined. (3) The effects of impurities on n-type, P-doped Si will be determined; these data will be compared with those for p-type, B-doped Si material. (4) The impurity matrix for n-type Si will be expanded, especially in two areas: measurement and modeling for material containing two or more impurities and study of impurities which may contaminate the Si during the Si production process. (5) The effects of oxygen and C interactions with the impurities will be studied.

2) Measurements of the Effects of Impurities on Solar Cells - Spectrolab. In this contract impurity doped ingots are used as material for the fabrication of solar cells by established processing. Performance measurements are used for analyses.

3) Effect of Impurities - C. T. Sah Associates. Deep level transient spectroscopy measurements are to be used for correlations with the development of a model for solar cell performance.

c. Processes for Producing Solar Cell Grade Si.

1) Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Process - Dow Corning. The Dow Corning contract is for the development of a process for improving the purity of Si produced in the arc furnace by using purer raw materials and for the further purification of the Si product by unidirectional solidification.

2) Production of Si from H_2SiF_6 Source Material Using Na Reduction of SiF_4 Process - Stanford Research Institute. The contract with Stanford Research Institute is for the development of a two-step process for the production of Si. The steps are (1) the reduction of SiF_4 by Na to produce high purity Si and (2) the further purification of this product.

3) Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na - Westinghouse Electric. This contract with Westinghouse is for the development of an electric arc heater for the production of Si using the reaction for the reduction of $SiCl_4$ by Na. The first phase consists of a review of the chemical and engineering feasibility and the designing of a system for experimental verification; it includes four subtasks: reaction analysis, plasma reactor, reactor storage and injection, and product collection and effluent disposal.

4) Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of $SiCl_4$ - AeroChem Research. The objective of this program is to determine the feasibility of high volume, low-cost production of high purity SiH_4 or solar-cell-grade Si using a nonequilibrium hydrogen atom plasma jet. Reactions of hydrogen atoms in the plasma jet with chlorosilanes are being studied.

5) Production of Si Using Si Halide-Alkali Metal Flames - AeroChem Research. The objective of this contract is to determine the feasibility of the use of flame reactions involving Si halides and alkali metals for producing Si in a low-cost, high-volume process.

6) High-Velocity, Continuous Flow Reactor for Producing Si - Schumacher. The objective of this contract is to determine the feasibility of using bromosilanes as the appropriate intermediates in these reactions to produce Si.

d. Supporting Contracts

1) Evaluation of Si Production Processes - Lamar University. The objective of this contract is to evaluate the potentials of the processes being developed in the program of the Silicon Material Task. The economic evaluations will be based upon analyses of process-system properties, chemical engineering characteristics, and costing-economics. The evaluations will be performed during all phases of the Task, using information which becomes available from the various process development contracts.

2) Impurity Concentration Measurements - National Bureau of Standards. Methods for measurements of impurities at ppba levels are to be developed.

3) Model of Si-Producing Reactions - AeroChem Research. This contract is for the formulation of a model and a computer code for the description of several of the Si processes now under development.

5. Summary of Progress

a. Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of Silicon Chlorides - AeroChem Research. The objective of this program is to determine the feasibility of the production of high purity silane or solar-cell-grade silicon using a nonequilibrium hydrogen atom plasma jet. Reactions of hydrogen atoms in the plasma jet with chlorosilanes are being studied.

In this quarter, the experimental apparatus was modified to achieve better defined conditions for depositing films on substrates and more accurate control of reactant feed rates over a broader range than previously used.

Since a major problem has been to obtain good mixing of H_2 and chlorosilane in the plasma jet, a new nozzle was designed and built which allows chlorosilane vapor to flow into the H/H_2 jet from an annulus surrounding the jet. This configuration is expected to provide good mixing while still maintaining jet integrity. Tests employing chemiluminescent reactions confirmed that these goals were achieved.

Various analytical techniques were used to evaluate the deposits produced in the tests and the following conclusions were drawn from the work in this quarter: Large quantities of chlorine (1.7 to 30 mole %) can be present in silicon films which will have a metallic silicon appearance. Amorphous, polycrystalline, and some preferred-growth silicon deposits were obtained, as indicated by X-ray defraction. Infrared spectroscopy is useful in detecting the presence of polymer containing Si, H, and either Cl or O. Conductivity measurements employing either direct current or RF techniques may be useful for determining film purity and monitoring discontinuities.

b. Production of Si by Hydrogen Reduction of Bromosilanes in a High-Velocity, Continuous-Flow Reactor - J. C. Schumacher. The objective of this contract is to determine the feasibility of using bromosilanes in a high-volume, high-velocity, continuous-reduction process for producing solar-grade Si. Preheated streams of H_2 and bromosilanes are the reactants, and preheated Si particles fed to the reactor serve as deposition sites.

The system employs multi-pass heat exchangers of quartz for preheating the reactants to temperatures as high as $1500^{\circ}K$. The designs were verified by constructing heat exchangers of Pyrex and conducting experiments first with nitrogen gas and then with the reactants H_2 and $SiBr_4$. These experiments also verified that $SiBr_4$ would not undergo decomposition when heated to temperatures as high as nearly $1373^{\circ}K$, an important consideration since the design of the system was based on the requirement that the reactants be preheated to high temperatures.

Five preliminary experimental tests were conducted with the apparatus at reactor temperatures ranging from 1113 to $1183^{\circ}K$. These experiments led to several modifications of the reactor/mixer. Although none of the experiments produced any silicon particles that could be collected, in two of the tests silicon deposits formed on the reactor wall where the reactant streams merged. The test results indicate that at temperatures of $1182^{\circ}K$ and above, Si can be expected to form at H_2-to-$SiBr_4$ mole ratios of about 15.

Future work will be devoted to a study of the chemical reactions taking place in the reactor, and to establishing the optimum parameters for the process. $SiBr_4$ and $SiHBr_3$ will be the main reactants.

c. Production of Si by SiF_4/SiF_2 Transport - Motorola. The Motorola process involves the conversion of metallurgical-grade Si (mg-Si) into semiconductor-grade Si(sg-Si) via a three step process utilizing SiF_4 as a transfer agent.

The conversion of $(SiF_2)x$ polymer was studied further in this quarter. Data from mass spectroscopy measurements showed that at temperatures greater than 400°C the main constituent gas phase is SiF_4, which is consistent with the conversion of the homologue residues into Si. A low product yield, resulting from partial disproportionation, was obtained due to insufficient residence time. A batch-type process apparatus was used to determine the efficiency and mass balance of the homologue conversion as well as reaction stoichiometry. In this apparatus the polymer conversion efficiency averaged 59% over twelve runs ranging between 52% and 89%. The wide range was believed to be caused by unequal residence times. Mass balance calculations over three runs ranged between 76% and 93%. The stoichiometry based on four recent runs ranged between 0.84 and 1.02, indicating that one mole of SiF_4 is generated per mole Si formed.

Near-continuous apparatus capable of producing at least 25 gm/hr of Si was also used. An average rate of 17.6 gm/hr of Si, attained over a 165 minute period, was obtained in seven runs. Although the operating parameters have not been optimized, an overall process efficiency of 78.5% was reported.

An economic analysis of the process was made based on preliminary material and energy balances and assuming a fixed capital investment of $10 million. The estimated manufacturing cost is $8.96/kg of Si for a 1000 MT/Y facility.

d. Production of Si Using Submerged Arc Furnace and Unidirectional Processes - Dow Corning. In this process high purity quartz and C are being used as raw materials for an electric arc furnace and the Si product is purified further using unidirectional solidification. The impurity elements of particular interest now are B and P. The main source of these impurities is the C-reductant. In this work charcoal was selected over other carbons because of its relative high purity. However, difficulties have been encountered in smelting with purified charcoal. Apparently, the charcoal structure had undergone a structural change during the purification with halogen gases at elevated temperatures (1700 to 2000°C). In addition, the purification treatments have not significantly reduced the inherent B and P levels of the charcoal to their required levels of 2 and 5 ppmw, respectively. The identification of high-purity carbon reductants which are low cost and chemically reactive in an arc-furnace environment is under way.

A development-size arc furnace located at the Elkem facility in Norway was used to evaluate the smelting characteristics of high-purity raw materials. The yields of Si were low for four runs, indicating that a satisfactory high purity, highly reactive reductant had not been used. Composition analyses showed considerable reductions in concentrations of most impurities, the concentrations of B and P remaining high.

The Czochralski method was applied to purifying Si produced from the arc-furnace. A 25- to 30-mm-diameter ingot was pulled, leaving 30% of the Si remaining in the crucible. Emission spectrographic analyses of the seed and tang ends of the ingots showed all elements except B and P to be below the 10 ppmw detection limits. Analyses after float zoning yielded B and P concentrations of 10 and 12 ppm, respectively.

A cost analysis of the envisioned overall process was performed. A 3000 MT/Y arc-furnace facility was estimated to require $10 million in capital and have a manufacturing cost of $7.99/Kg of Si product.

e. Production of Si by Zn Reduction of $SiCl_4$ - Battelle. This contract is for development of a process for preparation of semiconductor-grade Si by the Zn reduction of $SiCl_4$ using a fluidized-bed reactor.

A detailed material and energy flow sheet for a 50 MT Si/year EPSDU has been prepared. The EPSDU will be located within an available structure at Battelle.

A narrative on the step-by-step analysis of the design and operation of the PSDF was written as an aid in reviewing and revising concepts as well as for uncovering items requiring more information.

A tentative design of the fluidized bed reactor for the EPSDU was made. It is to be constructed of graphite-lined stainless steel and to be provided with a coaxial or external zinc vaporizer. The dispersion support plate has 12 holes for $SiCl_4$ gas injection aligned on a ring about 0.25 the distance from the outer wall to the center. Zinc vapor will be introduced on an inner ring located 0.6 the distance from the outer wall and containing eight inlet ports. It is anticipated that an SiC coating will be needed on the graphite liner to minimize carbon contamination. The concept of using an SiC-coated graphite felt sleeve liner is also being considered because of the mismatch in thermal expansions between SiC and graphite.

A tray-type vaporizer requiring a low inventory of zinc is being developed. Differential heat-transfer calculations are being made for use in enhancing the tray-type design.

The experimental zinc electrolysis cell was modified to conform to the Bureau of Mines' electrode configuration by providing the cell with horizontal electrodes having slanted chlorine vent channels on the underside of the anode. In the intended process, the zinc produced in this cell by electrolysis of $Zn/ZnCl_2$ mixtures (byproducts from the fluidized-bed reactor) is recycled as a reactant raw material. Operation of the experimental cell has revealed the need for several design changes, including a liquid level indicator system and a greater free board above the salt mixture level to prevent loss of the mixture due to foaming and blowover.

The miniplant was operated to supply JPL with Si product for evaluation. The total quantity shipped was 2.2 kg.

f. <u>Impurity and Process Effects on Silicon Materials and Solar Cells - Westinghouse/Dow Corning</u>. The objective of this program is to investigate and define the effects of various processes, impurities, and process-impurity interactions on the performance of terrestrial solar cells.

During this quarter the effect of crystal growth rate on the effective segregation coefficient was investigated by comparing the performance of solar cells fabricated from crystals grown by the Czochralski technique with those fabricated from crystals grown by the web dendrite technique (10 vs 60 cm/hr). When this study was undertaken the effective segregation coefficients for web growth were postulated to be one or two orders of magnitude larger than for Czochralski growth. The impurity elements used were Mn, Fe, Cr, Ni, Ti, and V at concentrations of 1 to 3 x 10^{18} at/cc in the melt. The performance characteristics of cells made from the contaminated material were compared directly with cells processed concurrently from webs containing no added impurity. The results of these experiments indicate that no measurable degradation in cell performance is evident save for the impurities Ti and V, elements which drastically reduce minority carrier lifetime. A comparison of the relative efficiencies of Ti and V doped cells with previously determined relationships between impurity content and cell performance indicates that the solid impurity content in the webs must be $\sim 10^{14}$ at/cc so that the effective segregation coefficient is $\sim 10^{-4}$. These results indicate that the segregation coefficients for metals in web may be not too much larger than those for Czochralski growth.

Results on the combined effects of resistivity and metal contaminants on the degradation of solar cell performance show that there is little synergistic behavior and that most of the degradation in performance is due to lifetime reduction by the metal contaminant. The variation of solar cell parameters with B content (resistivities from 0.05 to 50 ohm-cm) in the absence of intentional contamination was first made. Cell efficiency went through a broad maximum at 0.2 to 0.4 ohm-cm resistivity; 0.2 ohm-cm was chosen for the impurity investigation. The impurity elements studied were Cr, Cu, and Mn. The performances of solar cells fabricated from these materials were compared with those fabricated from 4 ohm-cm ingots doped with approximately the same amounts of metal impurities. In general, there is a fairly close parallel between the two sets of data indicating that little synergistic behavior occurs and that most of the degradation in performance is due to lifetime reduction by the metal contaminant. The cell data for the low resistivity material show considerably more scatter than ususally encountered for high resistivity material processed by the usual method. This suggests that other effects, such as precipitation, may contribute in a random fashion to reduce cell output.

A detailed analysis of the dark current-voltage characteristics of solar cells was applied to solar cells doped with specific impurities. The procedure makes it possible for the solar cell parameters affecting cell performance to be separated. These solar cell parameters are the series resistance, the shunt resistance, the bulk diffusion current, and the junction excess current. In general, the impurities used in this study did not influence the series or shunt resistance significantly, but instead altered the bulk lifetime or the junction excess current. Most impurities, including Ti, N, Cr, V, and Mo, cause cell performance degradation by a decrease in bulk lifetime. Cu starts to degrade the cell performance somewhat above a concentration of approximately 10^{16} at/cc. Unlike Ti, the Cu-induced cell degradation is largely due to an increase in junction excess current. Precipitates in ingots heavily doped with Cu have been observed and their presence in the high field depletion region can result in excess junction current. Fe degrades cell performance both by lowering bulk lifetime and by increasing the junction excess current. An analysis of the I-V curves for Cu, Mn, and Cu/Mn doped cells shows no synergistic effects.

Studies have been made on the effects of high temperature cycling on recombination lifetime. This work was done on high lifetime Si prior to studying gettering and annealing of impurity doped material so that changes in lifetime due to gettering, for example, can be clearly distinguished from those induced by the high temperature treatment itself or by excessively high cooling rates. The results obtained are consistent with the hypothesis that the number of defects present at a given quenching temperature can be described by Boltzmann statistics. Assuming that this model is valid, the activation energy for defect formation at high temperatures approaches 1.5 electron volts as determined from an Arrhenius plot.

g. Effects of Impurities - C. T. Sah Associates. The work on the transmission line equivalent circuit model of a solar cell has continued. A graphic display program was coded to display a cell parameter, such as lifetime, as a function of position in the cell at a terminal. This display capability is expected to significantly aid in the basic understanding of the parameters which control the efficiency of a cell under operating conditions. The steady-state lifetimes for short-circuit and near open-circuit conditions were graphed for one sun AM1 illumination for a p-on-n Au doped Si solar cell where the electron lifetime is 383 μsec and the hole lifetime 7.27 μsec. The results for this case show a complex behavior of the steady-state lifetimes as a function of position in the cell. The lifetimes are not simply related to the electron and hole lifetimes in the base region under low injection-level conditions as is to be expected from the simple minority carrier p-n junction theory of Shockley. It is noted that, in this example, the hole lifetime is approximately 30 times smaller than the electron lifetime. For the reverse case for the same Au acceptor recombination center in a n-on-p cell, the lifetime variations are expected to be very close to what one would expect from the simple Shockley low injection level theory. This illustrates the need for the development of an accurate model for solar cells and the characterization of recombination centers introduced by impurities in order to predict the effects of impurities on solar cell performance.

h. Production of Si Using SiH_4 Prepared by Redistribution Reactions - Union Carbide. In the SiH_4-effort studies of the kinetics and equilibria of the reaction for the hydrogenation of $SiCl_4$ the conversion to $SiHCl_3$ was shown to be substantially increased at higher operating pressures; these results greatly improve the practicality of the overall process. Yields of 25% at 100 psig were achieved at reaction times of under 15 seconds. The use of low-cost cement-Cu as a hydrogenation catalyst has given substantially identical kinetics as earlier Cu/Si alloys.

An integrated process development unit for converting metallurgical Si and H_2 to high-purity SiH_4 has been commissioned. Initial operation of the individual elements has followed designed performance. The hydrogenation section has been operated at up to 275 psig and has yielded equilibrium conversions to $SiHCl_3$ at under 15 second residence time. Initial corrosion studies have ruled out Ti as a construction material for the hydrogenation reactor at 500°C. Inconel 625 or 316 stainless steel are likely candidates pending further tests.

In the Si deposition effort a quartz fluid-bed reactor capable of operating at temperatures of up to 1000°C was designed, constructed, and successfully operated. During a 30-minute experiment, SiH_4 was decomposed within the reactor with no pyrolysis occurring on the reactor wall or on the gas injection system. A hammer-mill/roller-crusher system appears to be the most practical method for producing seed material from bulk Si.

In the first series of short experiments of a steelwall fluidized bed reactor, a bed temperature of above 100°C was produced, indicating that fluidized particles can be heated by high-frequency capacitive heating. As the bed temperature was increased a sudden, unexplained, drop in bed impedance at 32°C was observed; this instability is being analyzed. Tests were concurrently undertaken with a glass-wall reactor. A theoretical model has been incorporated into a computer program to determine regimes of stability and optimum operating conditions.

A total of 6.7 kg of Si powder was produced in two separate experiments in the free-space reactor without opening the reactor between experiments. No semisolid growth formations were observed on either the gas injector or on the reactor wall. In one experiment, a Si powder production rate of 2.8 kg/hr was maintained for one hour. The average particle size of the Si powder was increased from the typical submicron size to approximately 1.3 μm through modifications in the free-space reactor; non-spherical particles as large as 50μm were identified. A pellet cast from this powder had an electrical resistivity of 35-45 ohm-cm and was P-type conductivity.

Using a melt consolidation apparatus attached to the free-space reactor, powder was pneumatically transferred from the free-space reactor to the hopper of the melt consolidator at a transfer and melting rate of 0.8 Kg/hr. Rods, suction-cast from this melt, had P-type conductivity and an average electrical resistivity of 35 ohm-cm.

The process design for an EPSDU is under way. The first objective was the definition of a preliminary set of functional specifications for the overall process. For the SiH_4 production process, a Distillation Silane Process was formulated. Calculations indicate that this feature will produce ultra-pure SiH_4 without an activated-carbon trap. The process design work will be carried out on both the original process (Adsorption Silane Process -- ASP) and on the Distillation Silane Process (DSP).

Preliminary block flow diagrams and heat and material balances for every battery-limit stream were completed. Work on preliminary process flow diagrams and heat and mass balances for all process streams are in progress.

Conceptual designs have been initiated for the hydrogenation reactor, the free-space reactor, and the consolidation systems. The process design data available in-house and in the open literature reveal that additional data need to be acquired to perform a reliable heat and mass balance of the process. A preliminary list of needed data was compiled.

i. Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na-Westinghouse. This contract is for the development of an electric arc heater process for the production of Si based on the reduction of $SiCl_4$ by Na. The effort is in its second phase, which consists of a demonstration of the process at a Si production rate of about 100 kg/hr.

In this quarter a process engineering analysis was completed except for a small amount of work on purity analysis, and a design review was held. Information was compiled for a 1000-MT/year production rate on a recycle-type process, and a cost of $9.76/kg of Si (1975 $) was obtained. In the purity analysis effort, the equilibrium composition of liquid Si was calculated for the cases where either Fe, Cr, Mn, Al, V, B, or P impurities is present in the process feedstocks. Except for Al and P, most of these impurities end up in the product Si. About 15% of the Al and only a very small fraction of the P end up in the Si.

In late October, a serious problem arose in connection with the growth and separation of Si particles from the reaction stream. Previous calculations of the reactor length required for growth of the particles to the size required for inertial separation (5 micron diameter) were found to be in error. Later calculations indicated that reactor lengths in the order of 10 to 50 meters are required. Development proceeded at Westinghouse on both a condensation model (a homogeneous reaction case wherein the Si is condensed from the gas stream onto the reactor walls) and on a heterogeneous model. A conference was held at JPL on December 6, attended by representatives from Westinghouse, University of Minnesota, Oregon State University, Lamar University, Caltech, AeroChem Research Laboratories, J. C. Schumacher Co., Union Carbide Corp., and JPL to discuss the Si separation problem. This conference served as a basis for subsequent analysis of the problem.

The detailed design of the subsystems for the Phase II process demonstration was undertaken. Drawings of the modifications required for the facility were made, and work was started. Preparations of the facility to be used for the experimental verification equipment and the efforts for the supporting tasks of kinetics, injection methods, and reaction demonstration were begun.

j. Novel Duplex Vapor-Electrochemical Method for Silicon Production - Stanford Research Institute. The objective of this program is to determine the feasibility of using a two-step process in which Na is used to reduce SiF_4 obtained from H_2SiF_6, a byproduct of the fertilizer industry, to Si. The Si is further purified by a SiF_2 transport or an electrolysis reaction.

Preliminary estimates were made of the raw material costs for a proposed process in which: a 23% solution of fluorosilicic acid (H_2SiF_6) is converted to SiF_4 via Na_2SiF_6; SiF_4 is reduced by Na; salts are leached out of the product Si; and byproduct fluorides are converted to CaF_2 for waste disposal. The most advantageous estimate was the case in which tank car lots are used; HF is used for leaching and credit is taken for the fluoride salts.

The study of the reduction step was continued using a stainless steel reactor. A conversion rate of 40g/hr was reached. The morphology of the Si was determined by SEM, SEM/EDAX, and optical microscopy. Na and Si were shown to be present in the Si particles.

k. Studies of Process Feasibility and Economic Analyses - Lamar University. A major effort was focused on obtaining the data for the properties of Si source material for several alternate processes. The data list for vapor pressure, heat of vaporization, gas heat capacity, liquid heat capacity, and density is about 70% complete.

The preliminary calibration and evaluation of the apparatus assembled to measure the thermal conductivities of gases were completed. The experimentally determined values for the thermal conductivity of H_2 are in excellent agreement with values from the literature.

In addition, the experimental determination of thermal conductivity for Si-source materials was initiated. Preliminary results for silane (SiH_4) and dichlorosilane (SiH_2Cl_2) were reported in the temperature ranges of 25 to 300°C and 25 to 400°C, respectively. There have been no previously reported experimental data in the literature for gas phase thermal conductivity of these substances.

Major efforts were continued on the preliminary process design of the SiH_4 process (Union Carbide). The process flow diagram, material balance, and energy balance are 100% complete for the revised flowsheet (received from Union Carbide). Major process equipment design is 85% complete. The estimate of production labor requirements is 75% complete.

l. Silicon Halide - Alkali Metal Flames as a Source of Solar Grade Silicon - AeroChem Research. This program is designed to test the feasibility of utilizing continuous high temperature diffusion flames of alkali metals and silicon halides as an economical source of solar grade Si. Thermochemical calculations indicate that reactions between either Na or K and any of the silicon halides are strongly exoergic and that liquid or solid Si is the only condensed phase in any of the equilibrium product distributions.

The experimental effort on this program has concentrated thus far on $Na/SiCl_4$ and $K/SiCl_4$ flames in an evacuated reaction vessel. These flames are self-igniting, fast burning and intensely chemiluminescent. Solid reaction products have been collected, separated by simple washing, and some preliminary analyses performed. Spectroscopic characterization of the chemiluminescence has been initiated.

Vaporized reactants for the Na or $K/SiCl_4$ flames are obtained from two reflux columns (heat pipes) equipped with vapor outlets below the steady-state condensation points in the columns. Flows of 0.1 to 1.5 g min^{-1} K vapor are sustained by varying the reflux column pressure between 0.1 and 1.0 atm; the halide flow is controlled independently and made to match or slightly exceed the K vapor input rate. When the halide is provided in slight excess, reaction takes place about the boundaries of the K vapor stream.

The products of reaction are all solids and appear as a mixture of brown and white powders. Microscopic examination of the unwashed products reveals what seem to be agglomerates of particles with <1 μm diam. Washing with slightly acidic water removes the white powder (presumably KCl) and leaves a fine light brown powder. To date, the product has been retrieved simply from deposits on the cool reactor walls; no attempt has yet been made to collect the materials at high temperatures.

A tubular reactor for the preparation of larger quantities of products and possibly their separation via differential deposition is now being built. Provision is also being made for the addition of hot H_2/Ar diluents and variable flow rates and pressures in this reactor.

m. <u>Development of a Model and Computer Code to Describe Silicon Production Processes - AeroChem Research</u>. This program aims at developing a mathematical model and a computer code based on this model, which will allow the prediction of the product distribution in chemical reactors in which gaseous Si compounds are converted to condensed-phase Si. The reactors to be modeled are flow reactors in which SiH_4 or one of the halogenated silanes is thermally decomposed or reacted with an alkali metal, H_2 or H atoms. Because the product of interest is particulate Si, processes which must be modeled, in addition to mixing and reaction of gas-phase reactants, include the nucleation and growth of condensed Si via coagulation, condensation, and heterogeneous reaction.

The most recent version of a free shear layer turbulent mixing code (LAPP) which treats finite rate, gas-phase chemistry has been acquired and documented to ascertain exactly the numerous changes the code has undergone in recent years. Equations describing particle dynamics have been formulated and are being coded. A code for calculating particle coagulation rates is available; it will be recoded, combined with a nucleation model, and inserted into the LAPP code. A model for calculating nucleation rates has been selected from among several alternatives; the rate coefficients and thermochemical information needed for its utilization are currently being developed.

B. LARGE-AREA SILICON SHEET TASK

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the feasibility of several alternative processes for producing large areas of Si sheet material suitable for low-cost, high efficiency solar photovoltaic energy conversion. To meet the objective of the LSSA Project, sufficient research and development must be performed on a number of processes to determine the capability of each for producing large areas of crystallized Si. The final sheet growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

1. Technical Goals

Current solar cell technology is based on the use of Si wafers obtained by slicing large Czochralski or float-zone ingots (up to 12.5 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single crystalline Si wafers is tailored to the needs of large volume semiconductor products (i.e., integrated circuits plus discrete power and control devices other than solar cells). Indeed, the small market offered by present solar cell users does not justify the development of Si high-volume production techniques which would result in low-cost electrical energy.

Growth of Si crystalline material in a geometry which does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth, chemical vapor deposition (CVD), etc., are possible candidates for the growing of solar cell material. The growing of large ingots with optimum shapes for solar cell needs (e.g., hexagonal cross-sections) requiring very little manpower and machinery would also appear plausible. However, it appears that the cutting of the large ingots into wafers must be done using multiple rather than single blades in order to be cost-effective.

Research and development on ribbon, sheet, and ingot growth plus multiple-blade and multiple-wire cutting initiated in 1975-1976 is in progress.

2. Organization and Coordination

At the time the LSSA Project was initiated (January 1975) a number of methods potentially suitable for growing Si crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now being funded. After a period of accelerated development, the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from which the most cost-effective solar cells can be manufactured. The Large-Area Silicon Sheet Task effort is organized into four phases: research and development on sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype production development (1981-82); development, fabrication, and operation of production growth plants (1983-86).

3. Large-Area Silicon Sheet Task Contracts

Research and development contracts awarded for growing Si crystalline material for solar cell production are shown in Table 3-3. This work continued through the end of FY 1977. "Preferred" growth methods for further development during FY 1978-80 have been selected. By 1980, both technical and economic feasibility should be demonstrated by individual growth methods.

An economic analysis of the Czochralski ingot growth process was performed to assess its potential to meet near-term and 1986 goals. The study was made with the intention of identifying key features of the process that are making the process costly at the present time. The analysis, conducted at JPL and elsewhere, shows that a continuous growth process is necessary for cost reduction. It was decided to solicit proposals to develop an advanced

Table 3-3. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
SHAPED RIBBON TECHNOLOGY	
IBM Hopewell Junction, New York (JPL Contract No. 954144)	Ribbon growth, capillary die
Mobil-Tyco Solar Energy Waltham, Massachusetts (JPL Contract No. 954355)	Ribbon growth, EFG
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954376)	Ribbon growth, laser zone
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954654)	Dendritic web process
SUPPORTED FILM TECHNOLOGY	
Honeywell Corp. Bloomington, Minnesota (JPL Contract No. 954356)	Novel growth dip coating
RCA Labs Princeton, New Jersey (JPL Contract No. 954901)	EPI
INGOT TECHNOLOGY	
Crystal Systems, Inc. Salem, Massachusetts (JPL Contract No. 954373)	Heat exchanger method (HEM), cast ingot and multiwire fixed abrasive slicing
Kayex Corp. Rochester, New York (JPL Contract No. 954888)	Advanced CZ growth

Table 3-3. Large-Area Silicon Sheet Task Contractors (Continuation 1)

Contractor	Technology Area
INGOT TECHNOLOGY	
Siltec Corp. Menlo Park, California (JPL Contract No. 954886)	Advanced CZO
Texas Instruments Dallas, Texas (JPL Contract No. 954887)	Advanced CZO
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954374)	Multiblade slurry sawing
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954884)	Advanced CZO
CONTACT MATERIAL	
Battelle Labs Columbus, Ohio (JPL Contract No. 954876)	Die and container materials
Coors Porcelain Golden, Colorado (JPL Contract No. 954878)	Die and container materials
Eagle Picher Miami, Oklahoma (JPL Contract No. 954877)	Die and container materials
RCA Labs Princeton, New Jersey (JPL Contract No. 954817)	Die and container materials

Czochralski process, specifically one achieving continuous ingot growth through multiple use of crucibles, and incorporating improved sawing techniques. These techniques, when successfully developed, will reduce costs associated with crucibles, processing, and sawing losses.

4. Large-Area Silicon Sheet Task Technical Background

a. Shaped Ribbon Technolgy: EFG Method - Mobil-Tyco Solar Energy Corp. The edge-defined film-fed growth (EFG) technique is based on feeding molten Si through a slotted die as illustrated in Figure 3-1. In this technique, the shape of the ribbon is determined by the contact of molten Si with the outer edge of the die. The die is constructed from material which is wetted by molten Si (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm/min and a width of 7.5 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

b. Shaped Film Technology: CAST Method - IBM. The capillary action shaping technique (CAST) is based on the same principle as EFG growth (Figure 3-1); i.e., it utilizes a die constructed from material which is wetted by molten Si. Work under this contract is directed toward evaluation of the technical and economic potential of CAST for the preparation of Si ribbon. The effort concentrates on (1) understanding and extrapolating the effects of growth conditions, (2) characterization of the ribbon, with special emphasis on the correlation of structure and electrical performance, and (3) economic analysis of Si growth by this and other growth techniques.

c. Shaped Ribbon Technolgy: Laser Zone Growth in a Ribbon-to-Ribbon Process - Motorola. The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline Si ribbon (Figure 3-2). The polysilicon ribbon is fed into a preheated region which is additionally heated by a focused laser beam, melted, and crystallized. The liquid Si is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

d. Ingot Technology: Heat Exchanger Method - Crystal Systems. The Schmid-Vicchnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Figure 3-3). Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This eliminates the need for motion of the crystal, crucible, or heat zone. In essence this method involves directional solidification from the melt where the temperature gradient in the solid might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

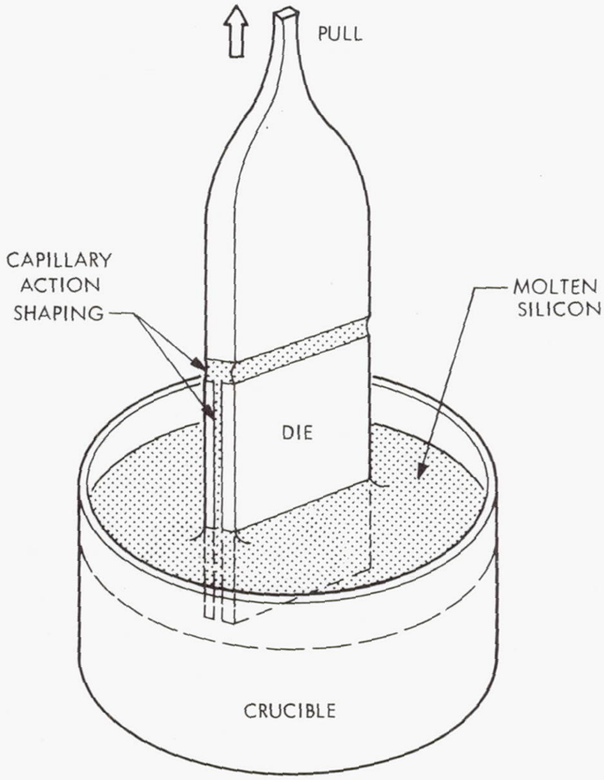


Figure 3-1. Capillary Die Growth (EFG and CAST) - Mobil-Tyco and IBM

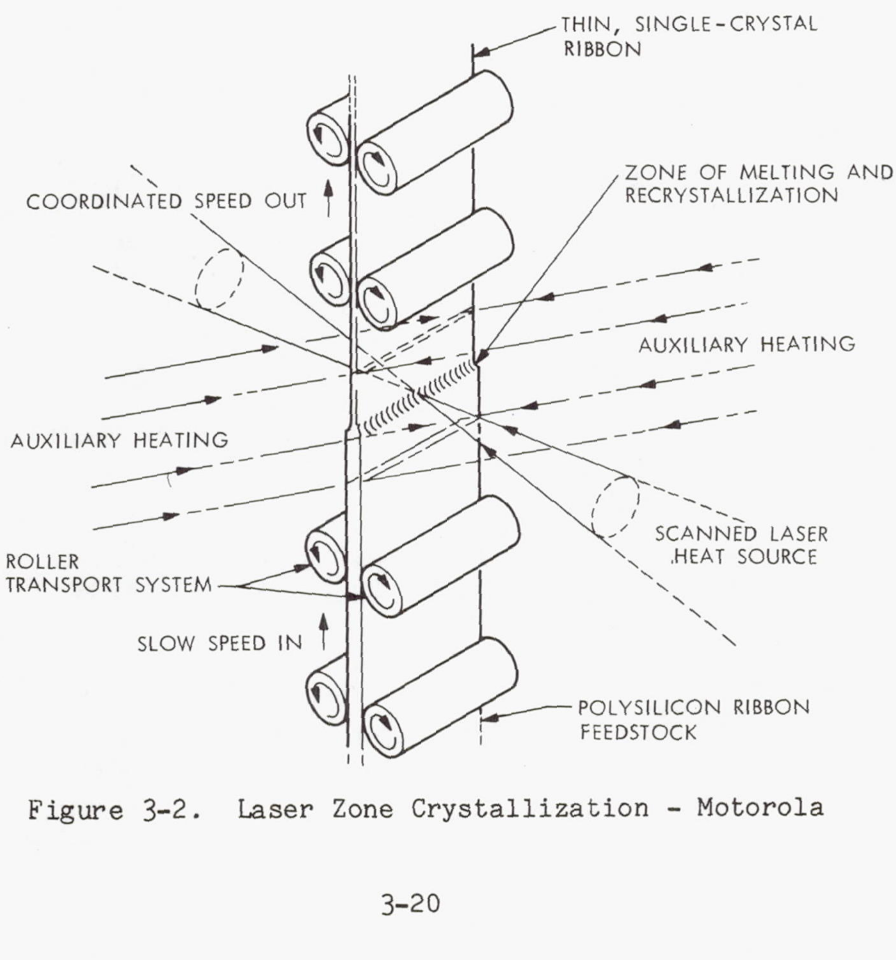
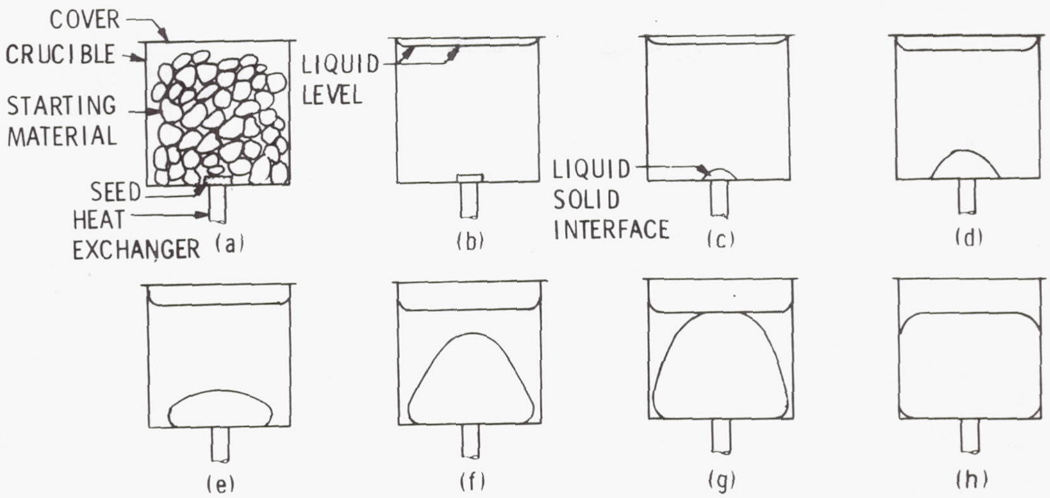


Figure 3-2. Laser Zone Crystallization - Motorola



Growth of a crystal by the heat exchanger method:
(a) Crucible, cover, starting material, and seed prior to melting.
(b) Starting material melted.
(c) Seed partially melted to insure good nucleation.
(d) Growth of crystal commences.
(e) Growth of crystal covers crucible bottom.
(f) Liquid-solid interface expands in nearly ellipsoidal fashion.
(g) Liquid-solid interface breaks liquid surface.
(h) Crystal growth completed.

Figure 3-3. Crystal Growth Using the Heat Exchanger Method - Crystal Systems

The overall goal of this program is to determine if the heat-exchanger ingot casting method can be applied to the growth of large shaped Si crystals (>8 inches cube dimensions) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire growth technology (50-pound ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for Si.

e. <u>Ingot Technology: Multiple Wiring Sawing - Crystal Systems, Multiblade Sawing - Varian</u>. Today most Si is sliced into wafers with an inside diameter saw, one wafer at a time being cut from the crystal. This is a big cost factor in producing solar cells.

The overall goal of the slicing program is to optimize multiblade (wire) Si slicing, investigating the following parameters in particular:

(1) Rate of material removal and kerf removal.

(2) Slice thickness, wire blade dimensions, cutting forces, wire/blade tension, and other machine variables.

(3) Wires versus blades as a cutting tool.

(4) Variation of workpiece rocking motion.

(5) Introduction of abrasive during slicing operation.

(6) Effect of surface condition of wire, including consideration of hardness and method of plating.

(7) Effect of abrasive particle size and type.

(8) Effect of cutting fluid composition.

The multiwire slicing operation employs a workpiece rocking motion with reciprocating wire motion and utilizes 50 0.2 mm wires. These are 0.5 mm steel wires surrounded by a 0.25 mm copper sheath, which is impregnated with diamond as an abrasive. The shape of the abrasives and their interaction with the copper and steel is an unknown variable and will be investigated. The individual wires within a multiple wire package are equitensioned by the use of a single jig in the form of a weaving machine.

The multiblade slicing opertion employs a similar reciprocating blade head motion with a fixed workpiece. Slicing is accomplished with a slurry suspension of cutting fluid and silicon carbide abrasive and tensioned steel blades of 6 mm height and 0.2 mm thickness.

The variables for slicing have been specifically identified. The independent variables are feed force, speed, rocking angle, and phase angle; the dependent variables are cutting rate, deflection, degradation of abrasive, and cut profile of y versus x.

5. Summary of Progress

a. Mobil-Tyco Solar Energy Corp. Further analysis of the EFG ribbon growth scenario using SAMICS interim price estimation guidelines show that a double 5-ribbon furnace of the general type represented by machine 3A operating under this contract can produce sheet material at <$20/m^2, the 1986 JPL goal. Technology requirements are:

(1) One operator for two 5-ribbon growth stations in which each ribbon grows at a speed of 7.5 cm/min at 7.5 cm width.

(2) Minimum duty cycle must be 67% and minimum yields 75%.

(3) Poly silicon material must be available at $10 to $25/kg depending on yield assumptions made.

The major problem encountered in the 7.5 cm wide by 7.5 cm/min ribbon growth is a severe tendency toward buckling at larger widths and higher speeds. Several design changes in the growth cartridge are being investigated to cure this problem.

Utilization of the fluid flow phemonenon during growth has shown that significant impurity re-distribution can be achieved. Proper utilization of this phenemenon in material grown from a "dirty" run has produced ~10% efficiency solar cells from the central 2.5 cm of a 5 cm wide ribbon.

b. IBM. The 100 mm-wide ribbon growth furnace has been installed. Thermal profiling of the graphite dies for proper operation of this machine is continuing. A 94 mm-wide ribbon was grown, but shattered upon withdrawal from the furnace.

Vitreous carbon and CVD Si_3N_4 were evaluated for die and material use.

Directional solidification of Si in a vitreous carbon crucible was achieved with grain sizes varying from 0.05 to 2 μm. The solidified silicon was found to be intact and free from cracks. Small SiC particles were found at the Si/C interface. Vitreous carbon has an equivalent thermal expansion coefficient as silicon in the range 650°C to 20°C. The degree of C contamination in silicon (20 ppm) is similar to the O_2 contamination of Si grown from SiO_2 (quartz) crucibles. However, C is not electrically active in silicon.

c. Motorola. Modifications to RTR #1 has increased laser output power. As a consequence, ribbon can now be grown at 10 cm/min (for 2 cm-wide ribbon stock). Accompanying this increase in growth velocity is a new growth phenomenon in the form of dendritic growth. The onset of dendritic growth is related to a critical velocity which is a function of the thermal environment. Non-dendritic growth can be achieved at velocities up to 7.5 cm/min.

RTR growth from a doped polyribbon feedstock obtained from a CVD process has been achieved. Initial diffusion length measurements of the ribbon obtained this way indicate equivalent performance to material regrown from single crystal feedstock.

Recent solar cell evaluation lots have shown metallization degradation to be the cause for low measured efficiencies (average of 7.7%).

Diffusion length studies on RTR solar cells have shown:

(1) Large diffusion lengths (>100 μm).

(2) Correlation between diffusion lengths and dislocation densities.

(3) Variation in diffusion lengths on grain boundaries.

The large diffusion lengths measured on processed cells contrast with the low values obtained from as-grown ribbons. The improvement occurs during the junction diffusion and AR coating steps.

d. Westinghouse. During this quarter the experimental phase of the program was oriented toward developing growth configurations which produced web crystals having low residual stress levels. Lid designs influence the web growth considerably: thick lids with narrow slots produce minimum temperature fluctuations and flat temperature profiles, but also produce high residual stress; thin lids with large slots minimize stress levels, but temperature fluctuations cause spontaneous web pullout.

Hybrid designs that reduce thermally generated stress while maintaining good melt thermal conditions are being developed with the help of the thermal modeling work accomplished in the previous quarter.

Economic analysis of the silicon web process concludes that the present area rate of growth capability (8 cm^2/min) needs to be increased by a factor of 2 to 3 in order to satisfy the 1986 cost goals.

e. Varian Associates. During the last quarter, fabrication was begun on a prototype large capacity multiple blade slurry saw. Final concept and design is nearly complete on a bladehead which will tension up to 1000 blades, and cut a 45 cm long silicon ingot of up to 12 cm in diameter. The large blade tensioning force of 270,000 kg will be applied through two bolts acting on a pair of "scissor toggles" significantly reducing applied torque to only 35 kg-m.

Poor wafering yields have caused concern in recent slicing tests. Perimeter fracture of slices have been the main cause of poor yield--this also impacts solar cell production yields of thin (250-350 μm) 10 cm diameter silicon slices. Recent tests with an "upside-down" cutting technique (in which the ingot is placed above the saw blades and cutting proceeds from the bottom up) has resulted in 100% wafering yields and highest wafer accuracy yet achieved. Additional slicing runs will be made to examine this technique further.

Variations in oil and abrasive mixes for low cost slurry so far have resulted only in degraded slicing results. A technique of continuous abrasive slurry separation to remove silicon debris and kerf was developed.

f. Crystal Systems, Inc. A Phase II add-on to the original contract was negotiated.

The crystal casting emphasis will be placed on examining heat flow and other thermal parameters to increase the growth rate of shaped ingots.

The crystal slicing portion of the program will continue diamond impregnated wire development along with further machine modifications to enable slicing of larger workpieces.

g. Honeywell. Seeding experiments performed during the quarter, where a small section of an EFG-grown silicon ribbon is used to seed an SOC coating, promoted significant improvement in single crystal grain growth.

Initial tests indicate that the bond between the silicon film and the substrate is actually stronger than the silicon coating itself.

Smooth continuous silicon coatings were applied to substrates which had flared slots cut into the "green" substrates prior to high temperature firing.

Modeling studies show that the series-resistance problem in slotted substrate cells improves considerably if the silicon does not penetrate the slots. The degree of penetration can be controlled by control of the carbonization of the slots.

Construction of the continuous coating (SCIM) machine was completed. Initial tests show the need for a few modifications. Thermal profiling tests are under way. The coater is designed to coat 10 cm by 100 cm substrates.

h. RCA. A new contract was negotiated this quarter for a program to develop and apply epitaxial growth techniques to the fabrication of efficient solar cells on low-cost forms of silicon sheet.

The work performed during the first quarter included the development of epitaxial machine; solar cell structures grown on conventional single crystal substrates, and initial studies of epitaxial growth and fabrication of solar cells on polycrystalline substrates (Wacker SILSO).

The results show that solar cells fabricated on epi layers of about 25 μm thickness can produce AMI efficiencies of 12%.

Growth studies on polycrystalline substrates were started and X-ray topographic studies of the epi layers show a substantially lower defect density in the grown layer. Some difficulties associated with the grain boundaries and height differences between grains were observed with the cells fabricated. Low open circuit voltages and fill factors are seen, however short circuit current densities are comparable to those for the single crystal cells. AM1 efficiencies up to 9.3% were measured.

C. ENCAPSULATION TASK

The objective of the Encapsulation Task is to develop and qualify a solar array module encapsulation system that has a demonstrated high reliability and a 20-year lifetime expectancy in terrestrial environments, and is compatible with the low-cost objectives of the Project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the array from the degrading effects of terrestrial environments. The most difficult technical problem is expected to be developing the element of the encapsulation system for the sunlit side; this element must maintain high transparency for the 20-year lifetime, while also providing protection from adverse environments. In addition, significant technical problems are anticipated at interfaces between the parts of the encapsulation system, between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections. Selection of the element for the rear side (i.e., the side opposite to the sunlit side) of the encapsulation system will be based primarily on cost, functional requirements, and compatibility with the other parts of the encapsulation system and with the solar cells.

Depending on the final solar array design implementation, the encapsulation system may also serve other functions, e.g., structural, electrical, etc., in addition to providing the essential protection.

At present, options are being kept open as to what form the transparent element of the encapsulation system will take - glass or polymer sheet, polymer film, sprayable polymer, castable polymer, etc. The transparent element may contain more than one material and may be integral with the photovoltaic device, or be bonded to it.

1. Organization and Coordination

The approach being used to achieve the overall objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts. The contractor efforts will be carried out in two phases. Within each phase some parallel investigations are being conducted to assure timely accomplishment of objectives.

During Phase I the contractor efforts and the JPL in-house efforts consisted primarily of a systematic assessment and documentation of the following items:

(1) Potential candidate encapsulant materials based on past experience with the encapsulaton of Si and other semiconductor devices and on available information on the properties and stability of other potential encapsulant materials and processes.

(2) The environment which the encapsulation system must withstand.

(3) The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.

(4) Test and analytical methods required to evaluate performance and predict and/or verify lifetime of encapsulant materials and encapsulation systems.

The result of this effort will be used to specifically define additional research, development, and evaluation required during the subsequent phase.

Throughout the task atypical or unique approaches to solving the encapsulation system problem will be sought and evaluated. For example, Phase I includes an evaluation of the feasibility of utilizing electrostatically-bonded integral glass covers as part of the encapsulation system.

In Phase II, contractor and JPL in-house efforts will be conducted to identify and/or develop one or more potentially suitable encapsulated systems and then verify the expected lifetime and reliability of these systems. Depending on the results of Phase I, the contractor effort in this phase will include an appropriate combination of some of the following items:

(1) Evaluate, develop, and/or modify solar module testing and analytical methods and then validate these methods.

(2) Perform materials and interaction testing, using these methods to evaluate candidates and demonstrate the reliability of encapsulation systems.

(3) Modify materials and processes used in encapsulation systems to improve automation and cost potential.

(4) Modify potential encapsulation system materials to optimize mechanical, thermal and aging properties.

(5) Implement research and development on new encapsulant materials.

2. Encapsulation Task Contracts

Encapsulation Task contracts are shown in Table 3-4. In addition, Professor Charles Rogers, Department of Macromolecular Science, Case Western Reserve University, serves as a consultant to this task (JPL Contract No. 954738) and will also implement selected supporting experimental investigations in the laboratories at Case.

Contractual negotiations in progress include follow-on contracts to the four major contractors, a contract with the Rockwell Science Center to study the interface characteristics of encapsulated solar cells, a contract with the Motorola Solar Energy Department to investigate the feasibility of developing antireflectance coatings for glass, a contract with Endurex of Mesquite, Texas, to continue the study of ion plating coating techniques, and a contract with Battelle to develop a life prediction testing plan for solar arrays at a specific deployment site.

3. Encapsulation Task Technical Approach

Program efforts to date have provided an assessment of the state of the art and a definition of the potential environmental and operational stresses imposed on the encapsulation system. A data base of candidate materials and their responses to these stresses is being accumulated and analyzed. Technology deficiencies are being experimentally exposed and documented.

a. <u>Evaluation of Encapsulant Materials Properties and Test Methods--Battelle: Study 3</u>. The experimental evaluations under Study 3 were completed during this quarter and the draft of the final report was begun. Efforts directed toward achieving the objectives of the study were broken down into several substudies encompassing both polymeric materials and glasses. Substudies identified with the letter "P" relate to polymeric materials; those identified with "G" relate to studies in which glass is a major component.

<u>Substudy P-1: Measurement of Properties of Polymeric Materials</u>

This study provides information on the tensile properties (modulus, strength, and elongation), thermal coefficients of expansion, moisture barrier properties, and light transmittance of candidate polymer materials in the as-received or prepared condition and after exposure to accelerated

Table 3-4. Encapsulation Task Contractors

Contractor	Technology Area
Battelle Labs Columbus, Ohio (JPL Contract No. 954328)	Environmental definition, materials evaluation, and testing
Case Western University Cleveland, Ohio (JPL Contract No. 954738)	System studies of basic aging and diffusion
Endurex Corp. Dallas, Texas (JPL Contract No. 954728)	Ion plating process and testing
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954773)	Encapsulation antireflection coatings
Rockwell International Anaheim, California (JPL Contract No. 954458)	Test methods and aging mechanisms
Rockwell Science Center Thousand Oaks, California (JPL Contract No. 954739)	Materials interface problem study
SPIRE Corp. Bedford, Massachusetts (JPL Contract No. 954521)	Electrostatic bonding process
Springborn Labs, Inc. Enfield, Connecticut (JPL Contract No. 954527)	Encapsulation test methods and materials properties evaluation

weathering (ultraviolet (UV) or thermal cycling). This information was used to help establish the aging resistance of the individual materials. The product of the tensile modulus and thermal coefficient of expansion was used, before and after aging, to estimate stress levels in materials laminates, as described by Carroll, Cuddihy, and Salama,* and indicate possible delamination at the encapsulant/cover/adhesive (or pottant) and adhesive (or pottant)/cell interfaces. Moisture barrier information was used in the selection of individual materials for use in encapsulant designs where barrier properties of the single component is critical. Light transmittance before and after environmental exposure was used to provide a measure of the utility of specific materials for cover applications.

<u>Substudy P-2: Evaluations of Polymer Subsystems and Interfaces</u>

Substudy P-2.1: Polymer Film Bonding. This study provided an evaluation of adhesive materials and the manner in which they are to be applied for use with the different polymer film material candidates (for the film-lamination encapsulation design), in order to reveal subsystems that are resistant to delamination and to moisture transport after test exposures to UV and to temperature cycling from -40 to 90°C.

Substudy P-2.2: Polymer Sheet Bonding. This study provided for polymer sheet candidates an output of the type described in Substudy P-2.1.

Substudy P-2.3: Cell Bonding/Sealing. This study provided an identification of adhesives and conformal coatings that are effective in protecting the metallic components of the system for moisture-induced corrosion. The effects of exposure of the materials to UV and temperature cycling are included in this substudy.

Substudy P-3: Polymer Encapsulation Systems Development and Evaluation

Substudy P-3.1: Polymer Film Lamination Design. Substudy P-3.1 provided information on candidate materials and procedures for the film-lamination type** of encapsulation design, which has significant potential for future low-cost arrays. The investigation included determination of (1) the effects of UV, humidity, and temperature cycling exposures on the output characteristics of the encapsulated cells and (2) the effects of encapsulation materials and processing on the electrical performance of encapsulated cells.

Substudy P-3.2: Polymer Sheet Bonding Design. This study provided for sheet laminates an output of the type described in Substudy P-3.1.

Substudy P-3.3: Polymer Conformal Coatings Design. This study provided for conformal coatings an output of the type described in Substudy P-3.1.

Encapsulated cells fabricated by laminating using selected films, sheets, conformal coatings, and adhesives have been prepared for evaluation before and after exposure to elevated temperature/high humidity, temperature cycling, and UV exposure. The effects of encapsulation and of aging on cell electrical performance were emphasized.

Specific cell parameters were measured in the as-received condition, after cleaning, after initial encapsulation, and after exposures to various environments (thermal cycling, UV, etc.) for a measured length of time. The parameters determined were

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*Carroll, W., Cuddihy, E., and Salama, M., Materials and Design Considerations of Encapsulants for Photovoltaic Arrays in Terrestrial Applications, IEEE Photovoltaic Specialists Conf., Baton Rouge, LA, Nov. 1976.

**Carmichael, D.C., Gaines, G.B., Sliemers, F.A., and Kistler, C.W., Materials for Encapsulation Systems for Terrestrial Photovoltaic Arrays, IEEE. Photovoltaic Specialists Conf., Baton Rouge, LA, Nov. 1976.

(1) Open-circuit voltage, V_{OC}.

(2) Short-circuit current, I_{SC}.

(3) Maximum power, P_{max}.

(4) Current at maximum power, I_{max}.

(5) Voltage at maximum power, V_{max}.

(6) Fill-factor (electrical), F.F.

(7) Series resistance, R_s.

(8) Shunt resistance, R_{sh}.

(9) Efficiency, in percent.

Because they form part of the optical path to the cell, encapsulants can affect profoundly the effective conversion efficiency of the photovoltaic module. Moreover, the service life of the cell is determined in a large measure by the choice of the encapsulant system. The critical measure of the utility of an encapsulant is its effects on the electrical output of the cells, initially and after exposure to service environments.

b. Experimental Evaluation of Accelerated/Abbreviated Encapsulant Test Methods--Rockwell International. All materials degrade, however slowly, on exposure to the weather. To meet the goals of the LSSA program, solar cell encapsulants must provide protection for 20 years. Consequently, the objective of the present program is to develop methodology for making confident predictions of encapsulant performance at any exposure site in the U.S. The inherent weatherability factors of insolation, temperature, and moisture must be considered.

c. Electrostatically-Bonded Integral Glass Covers--Simulation Physics. This is a program to develop integral glass encapsulation for terrestrial solar cells, using electrostatic bonding. The feasibility of this technique has been shown and functional demonstration modules have been delivered to JPL for testing.

Electrostatic bonding is a process through which a variety of dissimilar materials may be permanently joined without use of adhesives. With elevated temperature to produce ionic conductivity and an externally applied electric field to drive the mobile ions, irreversible chemical bonds are formed at the interface of the pieces being joined. The process is applicable to joining bare solar cells or those with a variety of antireflective coatings to glass and to joining glass to glass with the aid of inorganic interface layers. Compatibility of the process with solar cells and with associated array hardware has been fully demonstrated. Developmental modules have shown no degradation of solar cell performance caused by electrostatic bonding.

d. Polymer Properties and Aging--Springborn Laboratories. The goal of the program is to develop and test materials and encapsulation or coating processes suitable for the protection of solar cells to provide a minimum 20-year service life in a terrestrial environment. The work is being conducted at Springborn's facilities in Enfield, Connecticut, with cell performance being evaluated by Solar Power Corporation of Braintree, Massachusetts, under subcontract. The overall program is structured to include four other technical endeavors: cost analysis, selection of primers and enhancement of adhesion, upgrading ultraviolet stability, and processing repair studies.

e. Ion Plating Process and Testing--Endurex. Endurex has developed a high-energy-level ion plating process which has proven to be a cost-effective means of applying coatings to both plastic and metallic parts. The encapsulation of Si solar cells appears to be achievable by means of the ion plating process. Both cost-effectiveness and functional improvement are anticipated.

Since virtually any material can be deposited, the major objective of this effort will be the determination of which of several candidate materials is optimum for this application. Concurrent with the material selection will be a determination of its response to variation of parameters of the ion plating process. Bias voltage, deposition rate, and chamber pressure will have significant effects upon composition hardness and growth morphology. These will, in turn, affect such important cell parameters as active band width, antireflection, electrical conduction, abrasion resistance, thermal cycling, and environmental stability. These effects will be measured and noted.

4. Summary of Progress

Materials surveys continued at Springborn Laboratories to establish a list of candidate low-cost, long-life materials and materials design concepts that will meet the Project goals of \$0.50/watt for 1986. A goal of \$0.25/ft^2 has been established as a target goal for encapsulation materials. Significant findings and conclusions of these surveys are as follows:

a. Six construction elements were identified as common to all flat plate photovoltaic modules (although some elements may be missing or perform dual functions): top covers, superstrates (load-bearing), pottants, adhesives, substrates (load-bearing), and bottom covers.

b. Silicones, fluorocarbons, acrylics, and glass have been identified as the only inherently weatherable, transparent materials available at the present time. Commercially available silicones and fluorocarbons are too high-cost to show promise of meeting 1986 goals.

c. Acrylic polymers will not be recommended for substrate or superstrate functions. Based on wind deflection loadings, the thickness required for either function is 0.315 inch which, at a resin cost of \$1.42 per pound, calculates to \$1.77 per square foot. This figure exceeds the cost allocation by a factor of seven.

d. Currently, no commercially available acrylic elastomer exists that is suitable for use as a pottant. Acrylic rubbers are all copolymerized with acrylonitrile to improve oil resistance and are opaque. Some hot-melt adhesive acrylics are soft enough to provide stress relief, but the absence of crosslinking causes high creep and lack of resiliency. Development of a clear, pourable acrylic elastomer is required.

e. Due to difficulties encountered with solvent-based and emulsion polymers--such as solvent attack, drying cycles, and wetting--a protective film for laminating to module surfaces would be a useful innovation. This film would be produced by an extrusion process at a thickness of perhaps 2-4 mils and contain 5% ultraviolet screening compounds. A crosslinked form would probably have the highest durability.

f. Acrylic compounds for the LSA Project should be based on methyl methacrylate and butyl acrylate monomers. Resins made from these compounds have demonstrated the highest outdoor weatherability in tests performed by Rohm & Haas Company.

g. The ability to formulate ultraviolet screening coatings of low cost has been demonstrated. Using solution acrylic polymers (Rohm & Haas, Acryloid series) as vehicles, coatings of one mil thickness were found to have low, and in several cases zero percent, UV transmittance in the range from 290 to 350 nm. The cost of these coatings was in the order of $0.01 per square foot per mil.

h. The acrylic adhesives of choice belong to a class known as "second-generation" acrylics. They are characterized by ease of application, high bond strengths, rapid cure times, transparency, and low cost ($0.008/ft^2/mil).

i. Of the superstrate materials examined to date, glass is still the most cost-effective option at $0.25 to $0.30/ft^2.

j. In the survey of substrate materials examined to date, composites of wood and its by-products stand out as the most promising and cost-effective candidates. The high strength-to-weight ratio, known technology, and renewability of raw materials make wood attractive. A cost in the order of $0.12/ft^2 (particle board) makes this class of materials the least expensive yet found.

k. It is recommended that a study of wood product performance under actual weathering conditions be conducted, possibly including a survey of preservation techniques.

l. Honeycombs, cellular structures, and other various design concepts aimed at constructing very high strength-to-weight ratio materials need a strong emphasis.

Efforts during the following quarter will emphasize the following activities:

a. An in-depth study of the cost effectiveness of structurally designed materials such as honeycombs and extruded cell structures demonstrating high strength-to-weight ratios.

b. Continuation of investigations into inexpensive, load-bearing wood product substrates to discover the most cost-effective compostion.

c. An inquiry into elasticized and latex-modified cements to determine if any potential as a substrate exists.

d. The continuation of work on experimental UV-absorbing, transparent acrylic films, and coating formulations for the protection of pottants and substrates.

e. Continuation of the acrylic surveys and the securing of manufacturers' recommendations on specific grades of materials suited to construction element functions.

f. Experimental research and development program aimed at the synthesis of a transparent, pourable, room-temperature cure acrylic pottant. This material will be formulated to have processing characteristics similar to Sylgard 184 silicone rubber.

Studies were continued at Rockwell International to develop a methodology for making confident predictions of encapsulant performance at any exposure site in the United States. In the first year, emphasis was focused on the transparent encapsulant portion of universal test specimens (UTS) and on two films, Lexan polycarbonate and polystyrene. These results are reported in Rockwell quarterly and annual reports.

In continuation of the study, the power output of solar cells is being monitored in accelerated test conditions and in outdoor exposures. For this purpose, universal test specimens with nine different substrate/transparent encapsulant combinations were prepared. The objective is to predict outdoor performance from accelerated exposure data with photochemical stresses of eight times normal. Continuous accelerated exposure under eight key combinations of ultraviolet light intensity temperature and humidity for two months has been completed. Solar cell performance, which degrades due to moisture, now will be forced to the failure point by exposure of the UTSs to 100% relative humidity at 100°C.

A subsequent objective is to accelerate degradation rates by a factor of 100 or more. This includes the purely thermal reactions, such as hydrolysis, as well as the photochemical reactions. The photochemical acceleration is the more difficult problem. The use of natural sunlight avoids the problem of imperfect matching of the solar spectrum by lamps. However, it must be established how much the UV component of sunlight can be concentrated on samples without changing the degradation mechanism. Exposure of plastic films is planned at the Army's solar furnace at White Sands in February 1978.

Modifications to the electrostatic bonder are continuing at SPIRE. Equipment has been installed to permit a series of five continuous bonding operations. New platen pressure equipment which will permit a smoother, more uniform application of pressure has also been installed. A microprocessor and constant current/voltage equipment has been received and will be installed in the next quarter.

Four Type II electrostatically bonded (ESB) electrically functional modules were received from SPIRE. These modules have four 2 1/4 in. cells bonded to the front 6 in. x 6 in. glass. This sub-assembly was then bonded to a back glass that had been hollowed out except for a 1/2-in. wide bond strip around the circumference. Interconnections are welded silver ribbon. Plans are being made to expose these modules to natural and/or accelerated weathering with electrical testing at appropriate intervals.

A silicon solar cell without contact metallization was successfully bonded to Type 7070 glass by the ESB process with an open-mesh titanium-plated silver screen between cell and glass to perform as contact metallization. The screen employs approximately 1-mil diameter wire and is approximately 95% open. Cell electrical output was approximately 85% of a standard ESB cell. This promising result will be followed up with more development work.

Four experimental glasses from Corning being tested to replace Type 7070 glass for ESB showed poor results based on preliminary tests. Work is continuing on these and special Schott glasses.

Development of a suitable output terminal for use in Type III ESB modules is under way. Work in the planning stages include fabrication of Type III modules, and lap shear tests of various foils electrostatically bonded to glass.

Efforts at Endurex to ion-plate moisture and corrosion barrier coatings of various ceramic oxides have been only partially successful. The problem, recently recognized, is that cell metallization is highly porous, with capillary dimensions much greater than those of the ion-plated coatings. A good analogy is that the ion-plated coatings are lining the walls of caves but not sealing the entrances. Endurex, as part of its contract, was to investigate ion-plated metallization which should reduce ohmic losses caused by metallurgical bonding. Metallization produced by ion-plating should be essentially non-porous. Accordingly, program emphasis at Endurex is shifting to studies of ion-plated metallization, and then, subsequently, to the barrier coatings.

Rockwell Science Center investigations on RTV silicone rubber/glass bond strength demonstrated that the effect of moisture on adhesion can be predicted quantitatively. This methodology could be used in the development of water-insensitive adhesive bond materials. This adhesion study was extended to the RTV silicone rubber/silicon cell interface. Optimum surface treatments that remove less than 100Å of the original AR coating were developed. A UV source has been incorporated in the hydrothermal cycling chamber so the effect of photodegradation can be evaluated.

As a result of negotiated changes in the statement of work, Rockwell Science Center started a feasibility study on the use of ellipsometry and ultrasonics as possible techniques for non-destructive evaluation of adhesion in photovoltaic modules. The feasibility of using ellipsometric mapping to monitor changes during aging of a surface or interface was demonstrated. A new high resolution off-null procedure with spatial resolution of less than 0.5 mm was developed. The first ultrasonic analysis was performed on a JPL-supplied module and feasibility of locating and mapping of defects was demonstrated.

Case Western Reserve University completed experiments on the effect of UV exposure level versus temperature at 50% RH on nitrogen, oxygen, and moisture diffusion through methylmethacrylate-isoprene copolymer films. (Compositions: 100/0, 60/40, 45/55, 30/70, 0/100). Data are being analyzed. These results are expected to provide information on the potential for UV stabilization via copolymerization (as a possible improvement over blending). A follow-on study contract is being negotiated in order to expand the data base and to include studies under hygrothermal cycling conditions.

In-house work has included the following:

a. "Work of adhesion" tests were started. A test apparatus was constructed which can pressurize a cast film from underneath with an inert gas and thus create a small blister. The diameter of the blister can be maintained at any size by manipulation of the pressure. The work of adhesion is calculated from the gas pressure and the area under the blister. Various cast films, e.g., acrylic and silicone, will be subjected to various combinations of UV, elevated temperature, temperature cycling, and relative humidity to determine the effects of these environmental factors on bond strengths.

b. Calibration of Thunder Scientific Company humidity sensors was completed. Calibration of Panametrics humidity sensors is in progress.

c. The plans to expose samples of RTV-615, PVB, and Q3-6527 Silicone Gel to outdoor weather have been changed. Lewis Research Center has curtailed the original plans for exposure at seven sites to two sites because of budgetary limitations.

The two sites are the Panama Canal Zone and Mine's Peak, Colorado. The samples are in place at the Panama Canal Zone site. Exposure at the Mine's Peak site is planned when the weather improves.

d. Failure analysis, modification, and repair of large scale procurement modules has continued. Efforts included development of decapsulation methods, repair and resoldering of interconnects, failure analysis of cracked cells in Motorola modules, and analysis of causes of delamination in various modules.

e. Work has continued in the area of development of UV measurement and techniques, construction of an accelerated weathering chamber including UV, and studying the effect of UV on polymeric materials. Construction of the accelerated weathering chamber will be completed in the next quarter and will be fully described in the Eighth Quarterly Report.

SECTION IV

PRODUCTION PROCESS AND EQUIPMENT AREA

The objective of this area is to identify, develop, and demonstrate energy-conservative, economical processes for the fabrication of solar cells and arrays at a production price of less than $500 per peak kilowatt.

A. TECHNICAL GOALS

The goal is to develop and implement commercial, practical, low-cost, high-production, automated-rate processes for the conversion of silicon sheet material into solar cells and arrays.

B. ORGANIZATION AND COORDINATION

The Production Process and Equipment Area effort is divided into five phases, occurring over a 10-year period of time (Figure 4-1). The phases are:

I. Technology assessment.

II. Process development.

III. Facility and equipment design.

IV. Experimental plant construction.

V. Conversion to mass production plant (by 1986).

A milestone chart with major milestones identified is contained in Figure 4-2.

Phase I

As a result of Phase I (Technology Assessment) activities, a cell processing sequence with the attendant equipment and facilities required to achieve a solar module selling price of $2/watt by 1982 was presented and well received at the 8th Project Integration Meeting on December 7-8, 1977.

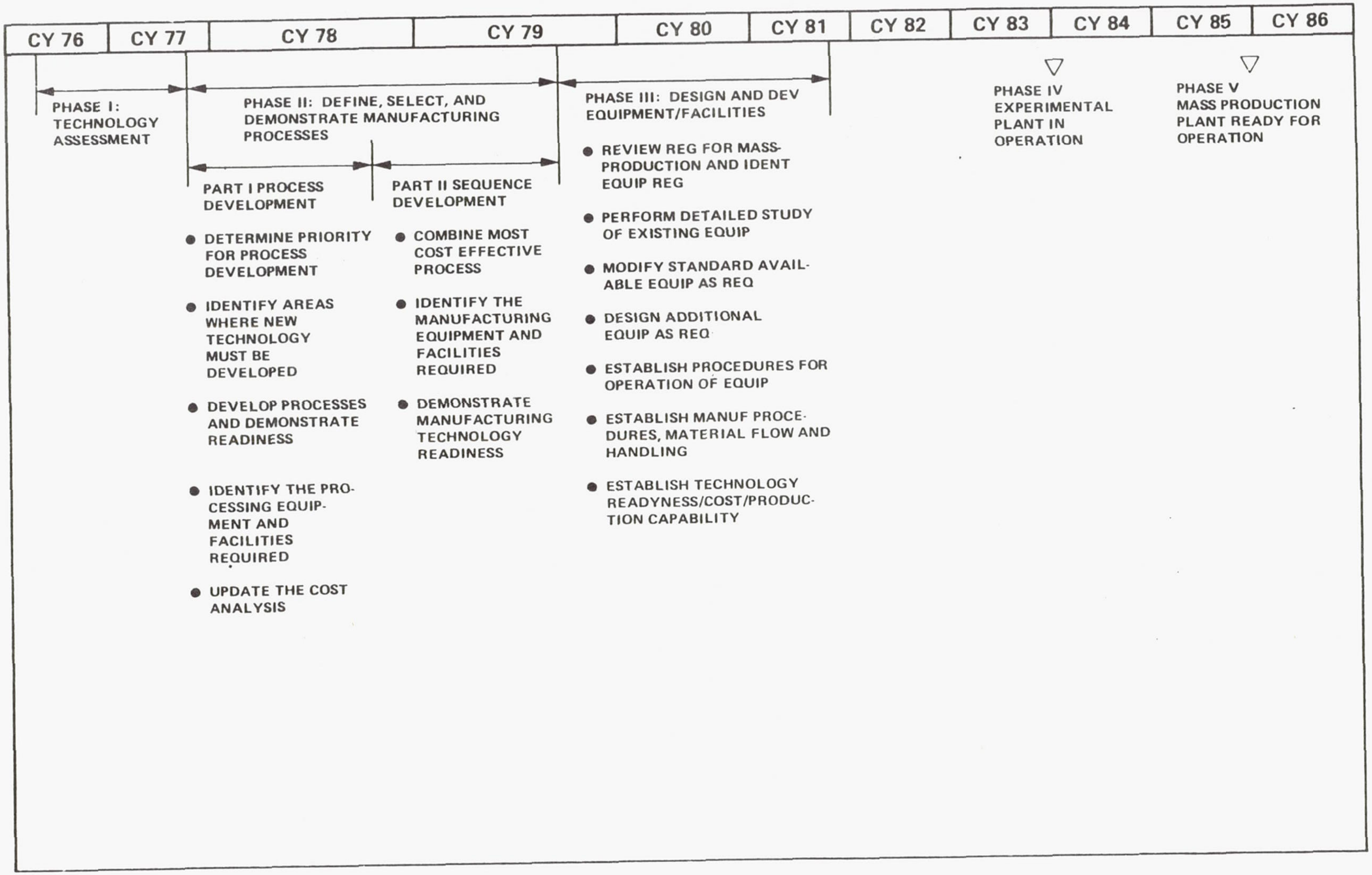

Figure 4-1. Production Process and Equipment Area Schedule

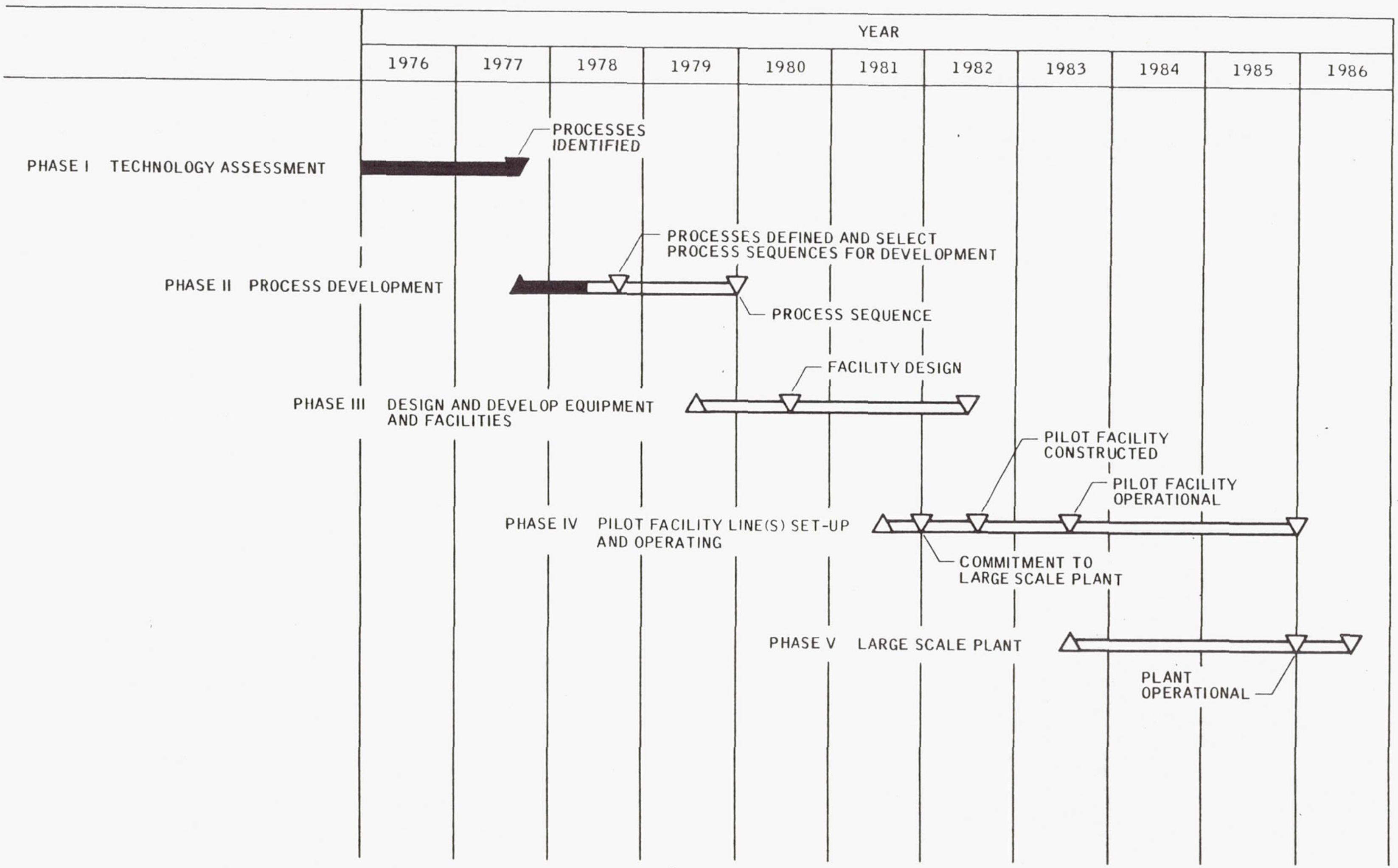

Figure 4-2. Production Process and Equipment Area Major Milestones

Phase II

Phase II, initiated in September 1977, will define, select, and demonstrate manufacturing processes. Part 1 will concentrate on Process Development with the following specific objectives:

(1) Determine priority for Process Development.

(2) Identify areas where new technology must be developed.

(3) Develop processes and demonstrate.

(4) Identify the processing equipment and facilities required.

(5) Update the cost analysis.

Contractors are shown in Table 4-1.

C. SUMMARY OF PROGRESS

1. Process Assessment Activities

The major thrust of the process assessment phase has been completed The results indicated that the development phase should be directed toward:

(1) Reducing material costs.

(2) Reducing supplies expense.

(3) Improving electrical efficiency.

(4) Reducing yield loss.

These results also indicated that labor and capital equipment will not be main cost drivers.

An energy assessment has been completed indicating energy consumed at each of the process steps.

2. Process Development Activities

Nine contracts of one year duration have been awarded for Phase II Process Development (see Figure 4-1).

The processing of a silicon sheet into a solar cell can be divided into three categories:

Table 4-1. Production Process and Equipment Area Contractors

Contractor	Type Contract	Technology Area
Arco Solar Chatsworth, California (JPL Contract No. 954751)		Panel Development Effort
General Electric R & D Schenectady, New York (JPL Contract No. 954607)		Shingle Type Modules
Lockheed Missile and Space Co. Sunnyvale, California (JPL Contract No. 954653)		Module Design and Fabrication
Lockheed Missile and Space Co. Sunnyvale, California (JPL Contract No. 954898)	Phase II	Process Development
MB Associates San Ramon, California (JPL Contract No. 954873)	Phase II	Process Development
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954363)	Phase I Add-on	Manufacturing Processes Assessment
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954689)		Metallization of Large Silicon Wafers
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954716)	Panel Development	
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954847)	Phase II	Process Development
Optical Coating Laboratories City of Industry, California (JPL Contract No. 954830)		Assessment of Slicing
Optical Coating Laboratories City of Industry, California (JPL Contract No. 954831)		High Efficiency Panel
RCA Princeton, New Jersey (JPL Contract No. 954352)	Phase I Add-on	Manufacturing Processes Assessment

Table 4-1. Production Process and Equipment Area Contractors (Continued)

Contractor	Type Contract	Technology Area
RCA Princeton, New Jersey (JPL Contract No. 954868)	Phase II	Process Development
Sensor Technology Chatsworth, California (JPL Contract No. 954605)		Hi-Efficiency Panels
Sensor Technology Chatsworth, California (JPL Contract No. 954865)	Phase II	Process Development
Solarex Rockville, Maryland (JPL Contract No. 954606)		Processing Energy Study
Solarex Rockville, Maryland (JPL Contract No. 954854)	Phase II	Process Development
Spectrolab, Inc. Sylmar, California (JPL Contract No. 954853)	Phase II	Process Development
SPIRE Burlington, Massachusetts (JPL Contract No. 954786)		Manufacture Cells with Pulse Processes
Texas Instruments Dallas, Texas (JPL Contract No. 954405)	Phase I Add-on	Manufacturing Processes Assessment
Texas Instruments Dallas, Texas (JPL Contract No. 954881)	Phase II	Process Development
Westinghouse Electric Corp. Pittsburgh, Pennsylvania (JPL Contract No. 954873)	Phase II	Process Development

(1) Surface preparation.

(2) Junction formation.

(3) Contacting systems.

Surface preparation includes damage removal from the sawing of the ingot, texturizing to reduce reflection losses, and optical coatings to reduce reflection losses. Damage removal and texturizing are sufficiently developed in the present state-of-the-art that significant additional development is not necessary.

However, optical coating development effort promises to accomplish multiple results in one operation. Motorola, for example, has a Si_3N_4 optical coating which is also used as the plating mask. Other optical coatings can be used for both antireflective and hermetic sealing purposes.

The general category of junction formation addresses the junction edge treatment, as well as the junction formation. In junction formation, development efforts are being concentrated on:

(1) Chemical vapor deposition.

(2) Polymer dopant.

(3) Ion implantation and anneal.

(4) Junction edge treatments including laser plasma etch, and mechanical. Additional effort is being directed toward the development of pulse energy processes.

Contacting systems include the metallization of the silicon as well as the joining of cells in solar modules. Silicon metallization development effort in Phase II is being concentrated on printing with thin film inks. Additional effort is being directed toward improved plated silicon metallization. Development effort directed toward the joining of cells includes:

(1) Wrap around contacts.

(2) Flame sprayed metal.

(3) Cell shaping and hole cutting.

(4) Gap welding.

3. Advanced Module Development

Advanced module development is being conducted to evaluate various design, manufacturing, and cost parameters. Modules under present development include emphasis on the following:

(1) Shingle type modules.

(2) Metallization studies.

(3) High transmission glass.

(4) Mechanical interconnect.

(5) Glass sandwich module construction.

(6) Cost effective manufacturing techniques (laser scribing and surface texturing).

(7) High efficiency (>13%), long life panels.

Typical development modules are shown in Figures 4-3 and 4-4. Figure 4-4 depicts high density modules from Optical Coating Laboratory, Inc., Solarex Corp., and Sensor Technology, Inc.

The shingle type of solar cells represents a unique application (Figures 4-5 and 4-6). A contract with General Electric for the development and testing of roofing shingle type solar cells involves the design, development, fabrication, and testing of a solar cell module which is suitable for use in place of shingles on the sloping roof of residential or commercial buildings. Modules of this type employ a semi-flexible substrate which is suitable for mounting on an independent rigid surface such as plywood roof sheathing. These modules are intended to be capable of producing an electrical power output of 80 W/m^2 of installed module area at a module temperature of 60°C with an insolation of 1 kW/m^2. The installed weight of these shingle type modules is less than 250 kg/kW of peak power output. As a design goal these modules are to bring designed leak-free service life of at least 15 years.

A shingle module, which employs a tempered glass coverplate as the primary solar cell structural support, has been designed. The evolution of this design concept is the result of the initial task activities which were completed during the first six months of the contract. Two separate module design concepts were advanced as possible candidate approaches. The first of these involved embedding the interconnected solar cells within a methyl methacrylate (MMA) casting which provided for encapsulation as well as the structural support for the solar cells. The second and final recommended design sandwiches the interconnected solar cells between a sheet of tempered low-iron glass on the front surface and a sheet of fiberglass/epoxy on the rear side. The solar cells are bonded to this glass coverplate with polyvinyl butyral (PVB) film and the interstitial space between the covers is filled with RTV 77, which functions as the primary encapsulant.

A set of detail drawings was prepared for each of these design concepts to enable the fabrication of a single preproduction module of each type for evaluation prior to the design review. An attempt to embed a 19-cell assembly, which had been previously buffer coated with RTV 615, within a MMA casting proved unsuccessful. This transparent silicone buffer coating, which was applied to elastically accommodate the thermal induced strains at the solar cell/MMA interface, turned cloudy upon the polymerization of the MMA and created an unacceptably large transmission loss. Bulging of the casting at the cell locations was also apparent upon reheating the casting. The volumetric thermal expansion of the RTV 615 was evidently sufficient to cause this permanent bulging and associated delamination at the RTV 615/MMA interface.

The preproduction module of the tempered glass covered design shown in Figure 4-6 was successfully produced.

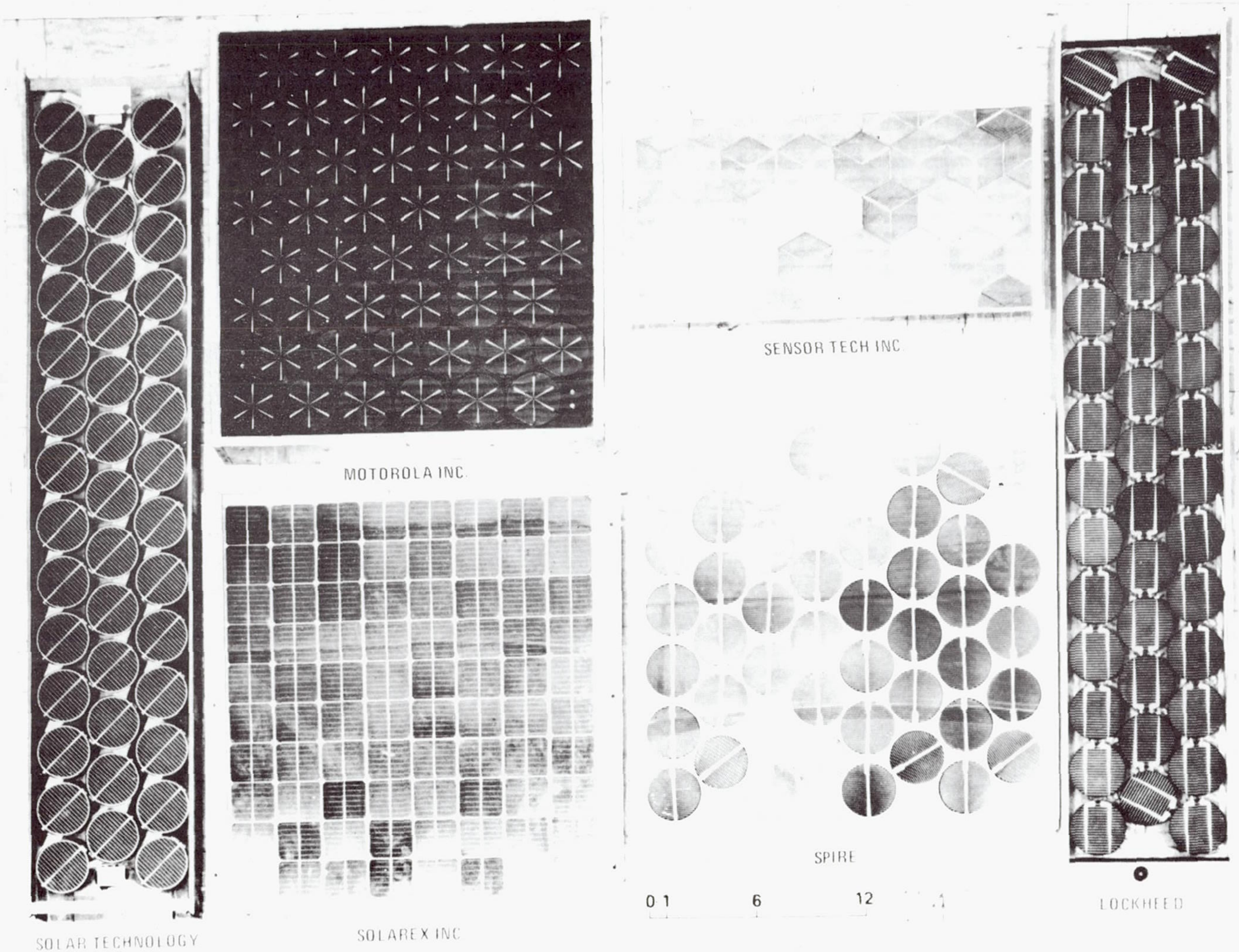

Figure 4-3. Typical Development Modules

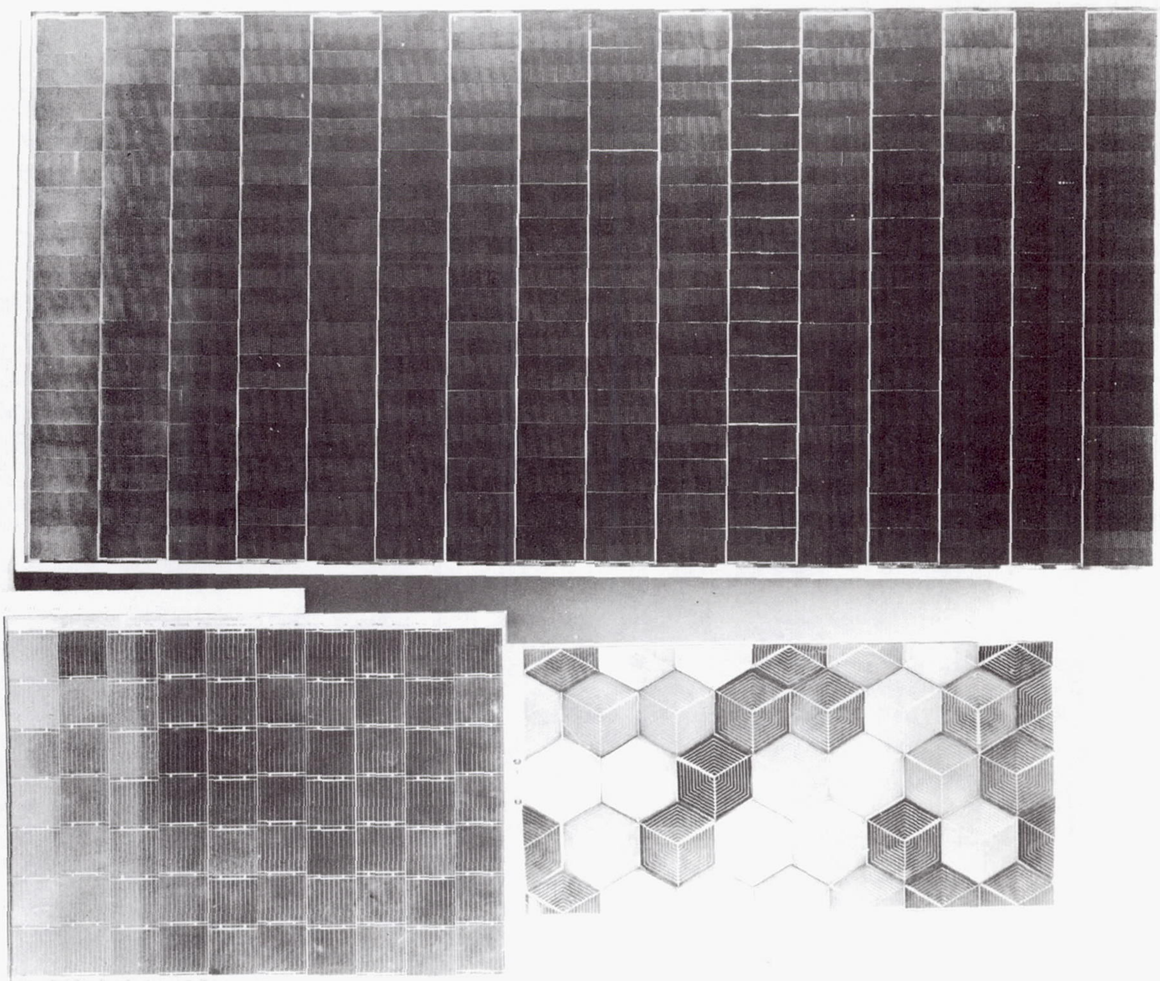

Figure 4-4. High Density Modules

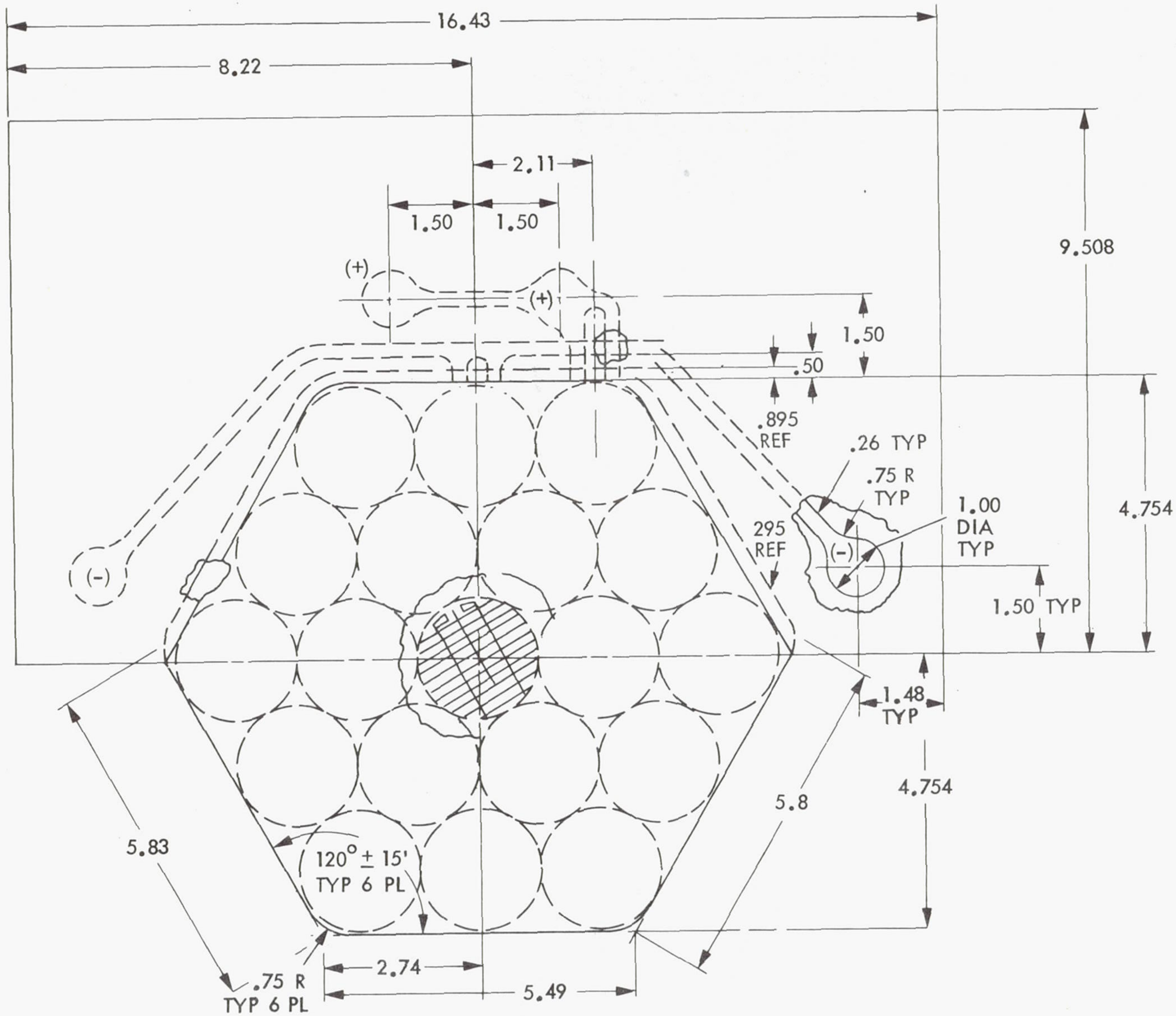

Figure 4-5. Shingle Type Solar Cell

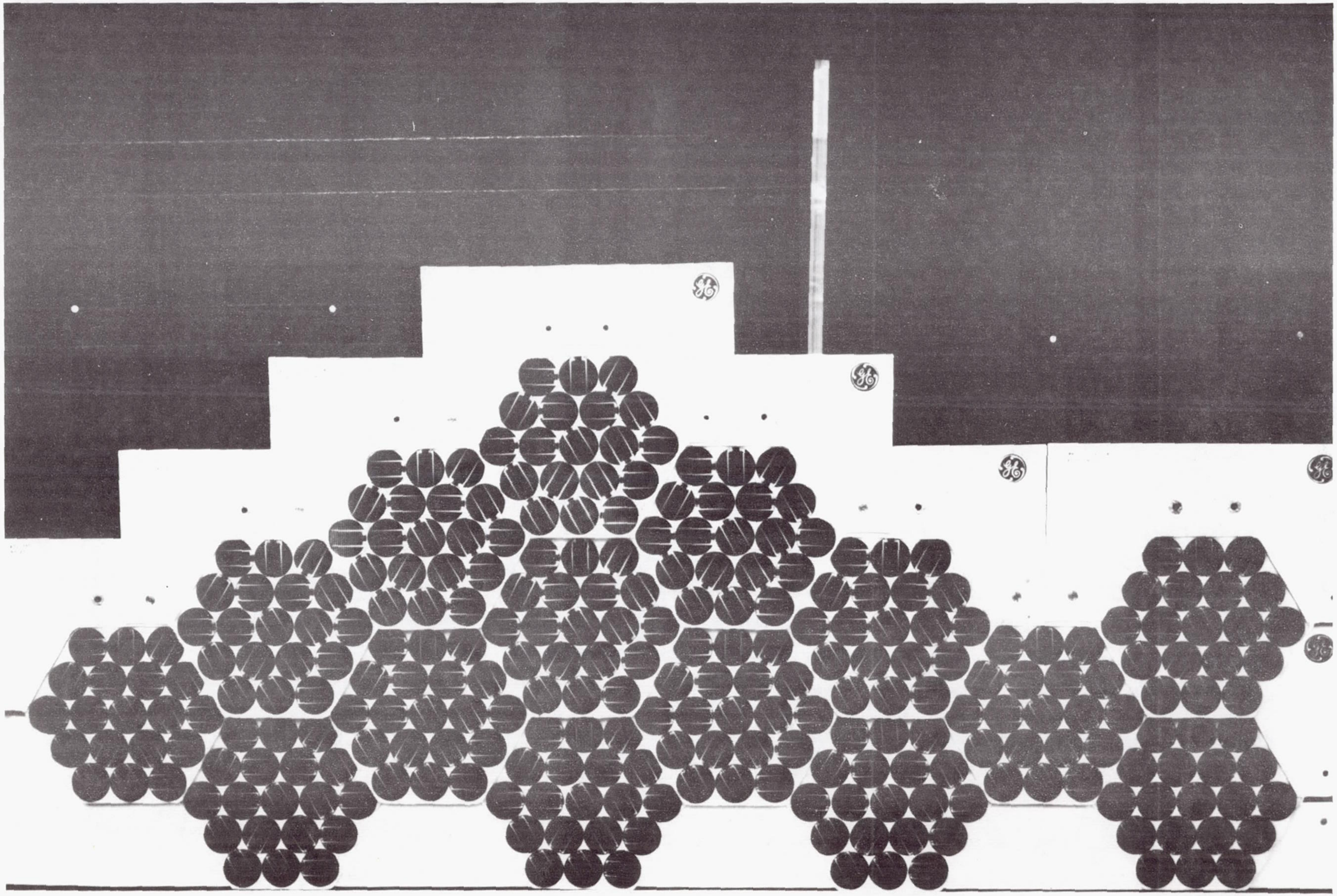

Figure 4-6. General Electric's Shingle Type Solar Cell

SECTION V

ENGINEERING AREA

During the quarter the Engineering Area has continued activities in the areas of (1) analysis and testing of solar array modules in conjunction with the development of future module and array design criteria and test methods, and (2) support of the large scale procurements in the area of engineering interfaces.

Module requirement contracts with Bechtel and Boeing started late last quarter and proceeded on schedule through the current quarter. The Bechtel contract is an add-on to its previous contract exploring module requirements for central power stations and is emphasizing optimization with respect to module structural costs. The Boeing contract is exploring the advantages and disadvantages of enclosing modules in a self-supporting transparent enclosure. During the quarter Boeing gathered information on solar cell covers (e.g., glass and spray-on plastic) in order to select a module design for use inside the air-supported enclosure. Two enclosure designs have been selected and, based on wind load evaluation, have been sized; detailed structure and thermal designs are being developed for these designs. Bechtel has been continuing work on glass modules. It has obtained glass data and solicited manufacturer's information on available sizes and sizing criteria.

Both Bechtel and JPL are using the non-linear stress analysis computer program ANSYS to provide improved sizing data for glass modules. Conventional linear, small-deflection theories overestimate the glass stress for a given wind loading by about a factor of two. The non-linear analysis allows a more accurate prediction of the actual principal stresses, and thus the selection of the minimum thickness glass. This work is in the process of being documented in a non-dimensional format for use by module designers.

In order to provide test hardware to support the development of improved environmental qualification test procedures, 60 reduced size versions of the Block II modules have been procured from each manufacturer. The individual modules, measuring approximately 12 by 15 inches, produce between 4 and 5 watts at various voltages depending on the number of cells. The manufacturing process, procedures, and materials; cell arrangement, spacing, and location; and interconnect configuration were required to be identical to the full size Block II modules. Shipments of mini-modules have been received from all vendors. Two mini-modules from each manufacturer were shipped to Desert Sunshine Environmental Test, Inc., to be installed on the large scale concentrator developed by DSET under contract to LeRC. It is anticipated that a minimum of four months exposure at 8:1 solar concentration will be obtained with these samples. A substantial cost savings results from using these smaller modules intead of full size Block II modules for destructive tests.

The testing phase of the hail test development study was concluded during the quarter with a series of high speed motion pictures (4000 frames/sec) taken of ice balls up to 3.8 cm (1-1/2 inches) in diameter impacting each of the Block I and II modules. A report documenting the testing phase is in preparation and will be released as an Engineering Area task report. Responses and comments were received from hail community experts on the preliminary draft of the hail environment/assessment (probability of being struck by hail of a given size) study report. The final draft reflecting these comments was released in November as JPL Report 5101-45, "Environmental Hail Model for Assessing Risk to Solar Collectors."

Thermal performance testing of various module designs is continuing. A summary of the Nominal Operating Cell Temperatures (NOCT) of the Block I and Block II modules has been prepared and typical values for module construction represented by these procurements are:

Module Construction	NOCT (^{o}C)
Finned aluminum substrate	40^{o}
Clear glass substrate	41^{o}
Aluminum substrate (no fins)	43^{o}
Fiberglass/plastic substrate	47^{o}
Double pane with air gap	60^{o}

A series of thermal tests has been conducted to evaluate the feasibility of combining an active water cooling system in the construction of photovoltaic modules. The tests demonstrated that a significant increase in module power could be obtained by cooling the modules with water. Power improvements of 11% and 20% were obtained with water inlet temperatures of 32^{o}C and 15^{o}C respectively. For those applications involving the movement of water (irrigation, swimming pool pumps, etc.) cooling the modules with the water should be given serious consideration.

JPL Report 5101-31, "Thermal Performance Testing and Analysis of Photovoltaic Modules to Natural Sunlight," was released for distribution to the photovoltaic community. This report describes measurements of the thermal performance of Block I and II modules. The appendix contains the JPL recommended method for determination of Nominal Operating Cell Temperature.

Studies were initiated this quarter on causes of delamination in module designs. The objective of the delamination test program is to correlate chemical or physical properties of the interface between encapsulant and substrate with the onset of delamination. Destructive tests measuring tensile, cleavage, and peel strength are being developed. Delaminated and bonded samples have been sent to Surface Science Laboratory in Palo Alto for analysis to obtain elemental and bonding information. As part of the delamination study a contract was placed with Truesdail Laboratories, Los Angeles, to perform a 1000 hour UV Weatherometer test. Samples consisted of one each of the mini-modules described. Very detailed color-corrected photographs and correct spectrally matched IV curves were taken for each module before initiating the test to serve as a baseline for UV induced delamination. Test results will be available early next quarter.

An investigation of module soiling characteristics was also initiated this quarter. A portion of this study involves a cooperative effort with the Los Angeles County Air Quality Management District (AQMD). The AQMD has eight air quality sampling sites which use a high volume particulate sampler providing data on total suspended particulates (TSP). JPL will place dust accumulation samples representing the various encapsulant systems at the Pasadena AQMD site. If a correlation can be obtained, the ability to characterize the dust environment at many potential photovoltaic sites will be enhanced, as the TSP equipment is in widespread use. The sample support rack has been fabricated and initial transmission data on the accumulation samples obtained. Investigation of the application of anti-static coatings and treatments to module encapsulants has also been initiated. One silicone rubber encapsulated mini-module has been coated with a fluorosurfactant anti-static solution, Zonyl FSC, manufactured by DuPont. This module and an identical uncoated panel will be exposed to the natural dust environment at JPL for up to three months, with comparative dust accumulation and electrical performances being periodically monitored. Several other coatings and additives mixed into the uncured encapsulant are also being investigated.

Engineering area representatives participated in the Department of Energy Photovoltaic Systems and Applications Workshop held in Reston, Virginia, on December 13-15, 1977. A paper entitled "Silicon Array Specifications and Near Term Performance Expectations" presented the most important module specifications being used by JPL including electrical performance, design configuration (interfaces), safety considerations, and environmental requirements. JPL Report 5101-43, "Module Efficiency Definitions, Characteristics, and Examples," was also distributed this quarter. This report provides detailed module efficiency definitions for use by the Program.

SECTION VI

OPERATIONS AREA

A. SUMMARY OF PROGRESS

1. Large-Scale Production Task

a. Block II. Module deliveries in this quarter totaled 10.6 kW. In this quarter, Sensor Technology, Inc., completed its contract and Spectrolab production provided most of the delivered modules. The overall record shows that 98.7 kW of the 124 kW total have been received by JPL for a completion of 70.3 percent. In December, Spectrolab, Inc., announced a corporate decision to deemphasize work in large scale production in favor of expanded research and development and concommitantly requested relief from its commitment to JPL for the Block II production. Negotiation in response to this request was scheduled for January.

b. Block III. During this quarter, the selection and allocation part of the procurement process for Block III was completed, the successful contractors were notified, and the allocation was announced. In December, the lack of DOE FY 78 funding permitted the implementation of contracts only to ARCO Solar, Inc.; Motorola, Inc.; and Solar Power Corp. It is anticipated that contracts with Sensor Technology, Inc., and Solarex Corp. will be implemented in January.

2. Environmental Testing

a. Large Scale Production (Task 5) Modules. Qualification tests for a total of 23 one-kW sample modules representing three suppliers were completed. Results were generally satisfactory for all modules. Some cell cracks were found in each type of module, including those of Manufacturer V, which has recently implemented an improved design to reduce cracking. A special series of progressive temperature cycling tests from +90°C to -40°C was made on four of the earlier Type V modules. It was hoped that a central band of temperatures safe from cracking could be found. However, the incidence of cracking was fairly well distributed over these temperatures.

Exploratory heat-rain and wind-driven rain tests were completed on modules from four vendors with acceptable results.

b. Task 4 Development Modules. Ten modules from Manufacturer U were tested at JPL. Five had aluminum cell back contacts and were in aluminum frames, and five had evaporated contact cells and were in stainless frames. The former gave appreciably less power and voltage. All passed the environmental tests satisfactorily, although a total of four cells cracked in the five stainless modules.

At the end of the quarter, the initial issue of a report on Task 4 testing (JPL Report 5101-49) was nearly complete. Distribution is expected by mid-January. Additional sections will be added to this report as Task 4 modules are received and processed.

c. Commercial Modules. Off-the-shelf modules from two manufacturers have been procured and tested. Since these were not bought to LSSA dimensions and specs, the qualification was abbreviated to temperature and humidity testing only. Modules from Manufacturer P passed these tests with only minor problems. However, five modules from Manufacturer Q had a 60% failure rate in tests. In addition, two of the ten modules received had low power output initially.

d. Cell Tests. Two hundred additional cells were received from Manufacturer W. Half were evaporated contact type (aerospace) and half were the improved printed contact type (Process B) used in the large scale production. After humidity tests, the aerospace cells showed very little change. However, the Process B cells' output appeared to improve by a few percent. This phenomenon is still under study.

3. Field Testing

The primary activity this quarter centered around the data system. After several major modifications to the system by the system contractor and some minor field rewiring by JPL, the system is now functioning to the point where it is possible to obtain I-V data on any module in the field.

In evaluating the dynamic load prior to the buy off, several tests were performed to determine if it was functioning according to the following purchase specifications: for current values below 200 mA, it must be accurate to ± 0.5% of the current value; for voltage levels below 2 volts, it must be accurate to ± 10 mV, and above 2 volts, within ± 0.5% of the voltage.

The conclusion from these tests is that the system meets or exceeds the purchase specifications. On December 19, the system was officially bought off. Deployment of all the Block I and II modules at JPL, Table Mountain, and Goldstone was completed by deploying remaining Spectrolab Block II modules. Installation of test stands at Point Vicente was delayed by procedural difficulties relating to off-Lab facilities work. Completion of this site is now expected during the next quarter.

4. Performance Measurements and Standards

The solar cell photon instability problem was studied at length during this quarter resulting in a better understanding of the problem. However, the necessary changes required in the manufacturing process to eliminate the problem have yet to be clearly identified and implemented. The three vendors involved at this time are Sensor Tech, Solar Power, and ARCO Solar. Cells from Solarex and Motorola have not exhibited the effect. The problem at this time appears to be primarily related to the fabrication process as opposed to a bulk material problem; however, each vendor's cells exhibit different types of effects necessitating an individual effort with each vendor. The current program involves: (1) systematic changes in the fabrication process and (2) the removal of wafers from selected portions of the process for completion in a fabrication line known to be clean at a different vendor's plant. Both Spectrolab and OCLI are participating in this latter effort since it has been established that their processes result in stable cells.

Standard cells from all Block III vendors except ARCO Solar have been delivered to LeRC for packaging and calibration. ARCO Solar cells have been delayed due to the photon effect that they have exhibited to date. Completed standard cells are scheduled to be delivered to JPL from LeRC by the end of January for checkout and distribution to the vendors.

Modification of the existing Large Area Pulsed Solar Simulator to increase the data throughput speed by a factor of three has been initiated and will be completed in March. The second LAPSS facility has been ordered and is scheduled for delivery in July. It is estimated that the combined LAPSS facility will become operational by the end of 1978.

5. Failure Analysis

Twenty-six Problem/Failure Reports (P/FRs) were filed during this quarter, and seven P/FR analyses were closed. About half the P/FRs filed were related to environmental testing and half were the result of field test or applications problems. Details of this activity are given in the Technical Data section which follows.

B. TECHNICAL DATA

1. Large Scale Production Task

a. Block II. The production detail for the quarter is shown in the table below:

	Total to be Delivered kW	Shipped Oct.-Dec. kW	Total Shipped through Dec. kW	% Complete kW
Sensor Technology, Inc.	40	0.8	40	100
Solar Power Corp.	15	0	15	100
Solarex Corp.	30	0	30	100
Spectrolab, Inc.	39.4	9.8	13.7	34.8
	124.4	10.6	98.7	79.3

Spectrolab has requested that it be permitted to terminate shipment after delivery of between 900 and 1050 modules or 23 kW to 27 kW.

b. Block III. During the quarter, the selection and allocation part of the procurement process for Block III was completed and three of the five contractors selected were put on contract. In early November, the selection and allocation action was seriously complicated by Spectrolab withdrawing its proposal. This required a reconvening of the selection and allocation committee to review the entire situation and to make a new allocation. This was completed and the contracts were negotiated as shown in the table below:

	Allocation kW	$/W IV-1977 60°C	Price $/W I-1975 28°C
ARCO Solar, Inc.	20	15.98	11.32
Motorola, Inc.	50	13.40	9.49
Sensor Technology, Inc.	40	16.00	11.52
Solar Power Corp.	50	14.50	10.53
Solarex Corp.	30	17.81	13.16
Total	190	* 15.20	* 10.96

* Weighted average

The price cited in the second column is the price in dollars per watt at the time of contract negotiation during the fourth quarter of 1977. The power is that measured or quoted at 60°C. The third column deflates the price from fourth quarter 1977 to first quarter 1975 and applies a correction to reduce the temperature to 28°C.

2. Environmental Testing

Table 6-1 summarizes environmental test results for the quarter for Large-Scale Production (Task 5) modules. Table 6-2 gives similar data for Automated Array Assembly (Task 4) developmental modules, and Table 6-3 applies to commercially available modules purchased off-the-shelf by the Project.

3. Failure Analysis

Table 6-4 summarizes the activity for Block I and Block II of Task 5 module test and application experience.

Problem categories for the P/FRs summarized in Table 6-4 are shown in Table 6-5.

a. Manufacturer V. Analysis of Block I module from the JPL Field Test showed an open circuit caused by a fractured interconnect at the module terminal.

Two Block II modules were returned from Mead, Nebraska (MIT/LL), one with open circuit and the other with degraded output. The open circuit was caused by both interconnects to the back of the cell not being soldered (Figure 6-1). The outer module suffered a cracked cell, causing severe power degradation.

b. Manufacturer W. Two Block I modules were returned from JPL Field Test because of open circuits. Modules are presently scheduled for analysis.

Four Block II modules were returned from Mead for analysis. One module presently being analyzed was found to have zero output; three others were returned because of exposed interconnects. Insufficient encapsulant coverage caused the interconnects to become exposed when subjected to cleaning in the field.

c. Manufacturer Z. Four Block I modules from JPL Field Test were analyzed. Analysis of one module showed cause of failure as fractured interconnects caused by inadequate stress relief. The remaining three modules appear to have similar symptoms.

Table 6-1. Environmental Testing at JPL, Task 5
October - December 1977

Vendor	Modules Tested	Module Type	Test	Elect. Degrad., %	Comments
V	5	Alum sheet, K-Type	Qual.	Ave.-1.6	Two modules showed two cracked cells each after temp. cycling. All modules showed terminal discoloration after humidity; also, one module has some delam. and split encapsulant.
W	6	Process B printed cells	Qual.	OK	One cell crack after temp. cycling.
Y	12		Qual.	OK	Minimal changes in temp. and humidity. Some small edge and radial cracks in two modules after MI (wind simulation).
V	4	Type H	Heat-rain Wind-rain	OK	Marginal electrical degradation in one module after heat-rain.
W	3	Type G	Heat-rain Wind-rain	OK	One cell cracked in heat-rain.
Y	4		Heat-rain Wind-rain	OK	No changes.
Z	3		Heat-rain	OK	One - marginal electrical degrad; one - terminal discoloration; one - encapsulant splitting.
Z	4		Wind-rain		All OK.

Table 6-2. Environmental Testing at JPL, Task 4
October - December 1977

Vendor	Number Modules Rec'd	Number Modules Tested at JPL	Module Type	Test	Elect. Degrad. %	Comments
U	6	5	Stainless frame	Qual.	OK	Three cells on one module and one cell on another cracked.
U	6	5	Alum back contact, al frame	Qual.	OK 1@-4%	Passed environmental tests well. However, these had 11% lower max power output than the stainless frame type. Also, alum. modules were inefficient at 15.8V and 60°C. They were derated to 14.7V.

Table 6-3. Environmental Testing at JPL, Commercial Modules October - December 1977

Vendor	Number Modules Rec'd	Number Modules Tested at JPL	Module Type	Test	Elect. Degrad. %	Comments
P	5	4		T, H~	OK	Extensive delam from back side of cells in temp cycling. This mostly resealed in humidity. One small cell crack. Several interconnects partially lifted off cells both front and back.
Q	6	3	Mylar back	T, H~	2 OK 1-55%	One cell was cracked on receipt of one module. Another cracked during temp cycling which probably resulted in electrical failure.
Q	4	2	Fiber-glass/ resin back	T, H~	1 OK 1-98%	Two modules had low power output as received (only 60 and 29% of average power of the remainder). One cell in one module cracked during humidity which probably resulted in -98% elect. degrad. A long edge-to-edge crack appeared in cover glass of another module plus encap delam.

Note:

No. MI, thermal coeff, flexing tests were run. No rigid mount was used.

Table 6-4. Summary of P/FR Activity

Manuf.	Procurement Block	New P/FRs	Closed P/FRs	Envir. Test	Field Test	Application Centers
V	Block I	1			1	
	Block II	2	2	2		2
W	Block III	2		2		
Y	Block I	2			2	
	Block II	6	2	4		4
Z	Block I	3	1		4	
	Block II	1	2	3		
P	Task 5	3		3		
Q	Task 5	4		4		
U	Task 4	2		2		

A Block II module undergoing environmental testing will be analyzed for power degradation after testing has been completed.

d. Manufacturer P. These commercially available modules procured by Task 5 were found to develop some cracked cells and delamination during qualification testing. Analysis will be conducted on a time-available basis.

e. Manufacturer Q. These modules, procured by Task 5 for comparative study, were also found to develop cracked cells, electrical degradation, and delamination. Only a cursory analysis of cause is planned.

f. Manufacturer U. Developmental modules procured by Task 4 are being analyzed to determine cause of cell cracking after temperature cycle.

Table 6-5. Problem/Failure Categories

Manuf.	Proc.	Electrical	Mechanical	Materials	Comments
V	I	1			Open circuit
	II	2		2	Open circuit, degradation. Termination hardware corroded
W	II		2		Cracked cells
Y	I	2			Open circuit
	II	1	5	2	Short circuit, cracked cells, exposed interconnects, terminations. Hardware corroded
Z	I	4	4		Open circuit, delamination. Fractured interconnects
	II	1		2	Degradation, termination. Hardware corroded
P	T5		2	1	Cracked cell, delamination
Q	T5	2	2	1	Degradation, cracked cells, delamination
U	T4		2		Cracked cells

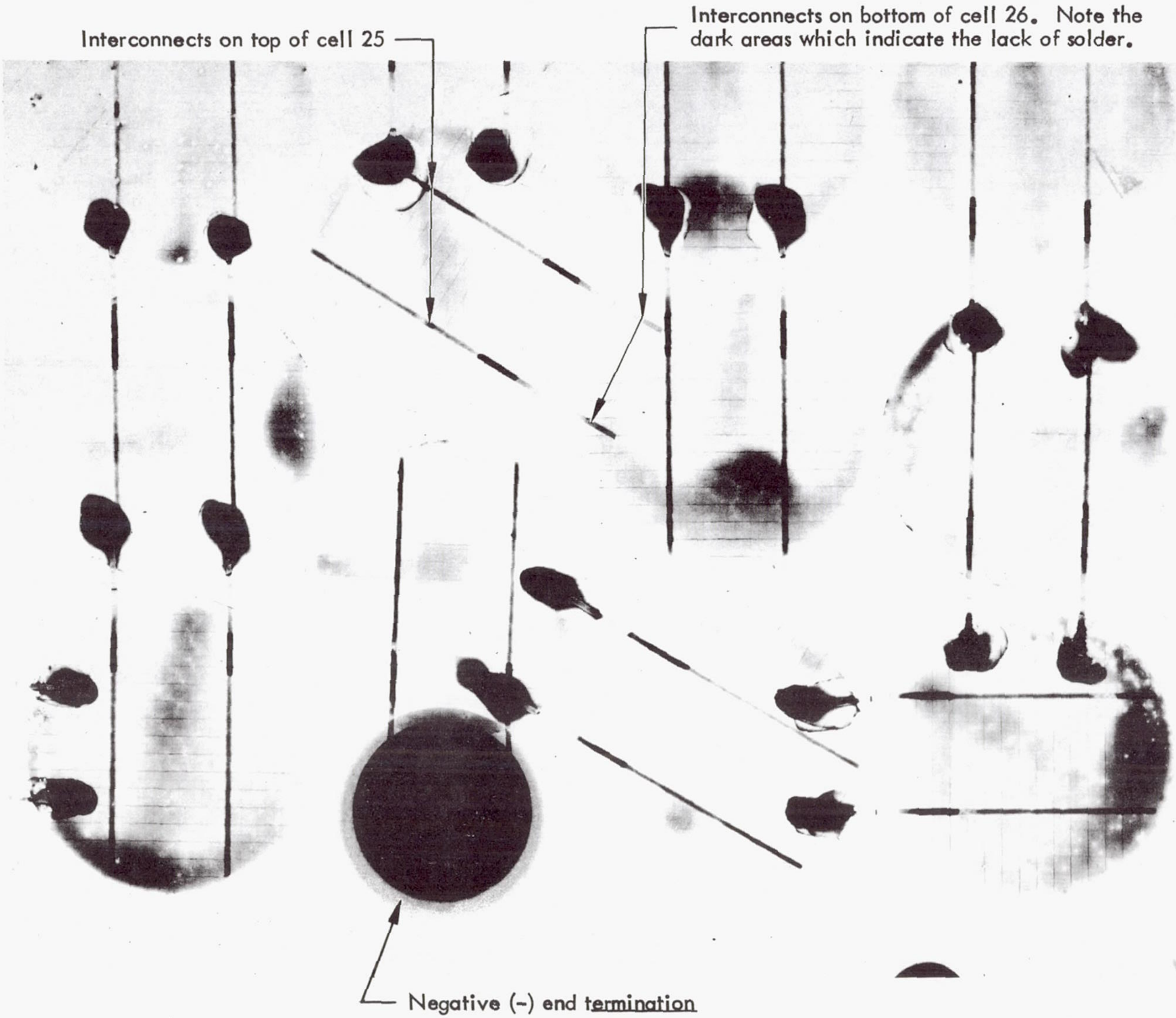

Figure 6-1. X-Ray Photograph of Manufacturer V Module

TECHNICAL REPORT STANDARD TITLE PAGE

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16. Abstract

This report describes research, development, and operations activities performed by JPL's Low-cost Solar Array Project and its contractors for the Department of Energy during the period October-December, 1977.

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